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PROCEEDINGS OF DETONATION WAVE SHAPING CONFERENCE

HELD AT
JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA
5 - 7 JUNE 1956

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FOREWORD

Although the study of detonation wave shaping is of fundamental importance in the design of nuclear weapons, it appears to have been relatively neglected in the area of conventional weapons. The timeliness of the meeting on detonation wave shaping is perhaps one of the more important reasons for its apparent success. Coupled with this, the availability of sufficient discussion time and the presence of key people in the field without too large an audience of "listeners" are believed to be additional factors contributing to the favorable reception.

Normally such meetings cannot profitably be organized every six months since their value depends largely upon the progress made by many different organizations since the last one. In the final analysis the most useful basis for assessment of the significance of such a meeting is the amount and qual' of the new research stimulated by it. In this respect the evaluation of the recent meeting remains incomplete. However since many who attended indicated that such stimulation for new research was provided, the quantity and quality of future reports from the various installations involved will constitute the final measure of significance of the meeting.

Louis Zernow

1

FUNDAMENTAL PRINCIPLES OF WAVE SHAPING

by

Melvin A. Cook

University of Utah

ABSTRACT

Principles of wave shaping and pressure-time or total impulse "shaping" are discussed in this article. The fundamental principles involved in wave front shaping are discussed under five types, each of which is illustrated by experimental results. The most important method currently in use involves interruption of the detonation wave under conditions where it may be re-formed (as high-order detonation) a time τ later. This time is temperature controlled and involves the heat balance of the explosive. The importance of the p-t contour behind a "shaped" wave front is discussed and illustrated by flat plate and rod studies.

INTRODUCTION

Wave shaping is of great importance in many modern explosive-actuated devices as well as in fundamental studies of explosive phenomena and impulse loading. Since wave shaping is useful principally in the impulse loading of targets, it is important to realize that successful wave shaping is not alone a problem of shaping the front of the detonation wave to impact the target in a predetermined way. A factor of at least as great importance as the shaping of the front itself is that of regulating and controlling the integrated pressure-time pulse or total impulse loading into the target at each element of its surface. The shape of the wave front can be easily determined by streak photography or pin techniques, but the determination of the nature of the pressure-time pulse is a far more difficult problem. The only experimental method for its study at present is the direct observation of the rate of acceleration and the terminal velocity of each element of the target (and the compressions and tensions set up in the target if they can be determined).

The principles underlying various wave-shaping techniques will first be discussed along with some experimental results. Then the nature and underlying principles of control of the pressure-time profile in detonation will be considered briefly both theoretically and in connection with experimental results obtained and obtainable by the use of flat plate and rod techniques.

SHAPING OF THE WAVE FRONT

The shape of the wave front may be regulated by the application of one or more combinations of the following:

1 Wave interrupters which require the wave to go around the interrupter. (These are, in general, inert fillers of such thickness that the shock wave emerging from the filler is too low in intensity to re-form the detonation wave.)

2 Two explosives of appreciably different velocity

3 Low order detonation

4 Density and composition variations in the explosive

5 Air and/or inert fillers of such thickness as merely to delay the wave but not completely destroy it. (Actually, this type will almost always also act as a wave interrupter but the shock wave emerging from the inert medium is of such intensity as eventually to cause re-formation of the detonation wave after a time lag τ.)

Type 1 was used in early shaped-charge work and proved successful in increasing the penetration of shaped-charge jets but decreased the hole volume produced in the target. The principle employed was simply to shape the wave front so that the wave impacted the liner as nearly normal to the surface as possible. This was accomplished by making the wave shape as near to the shape of the cone as possible. Figure 1 illustrates an assembly employing this type of wave shaper in which the wave shape was measured at 1.0 to 5.0 cm from the base of the interrupter. Note that the wave, while strongly inverted at first, reverted rapidly

toward the normal or steady state form which is a spherical cap (Ref 1). Results with shaped charges, using the assembly shown in Figure 1, demonstrated that if the apex of the cone was at a distance $x \leq 3$ cm from the base of the wave interrupter, some (5 to 10%) increase in depth is obtained but at a sacrifice of up to one-third or more in total hole volume. Somewhat better results in depth of penetration (perhaps up to 30% more than with no wave shape control), but with perhaps more loss in hole volume, may be (and have been) achieved by more careful regulation of the shape of the filler and distance to the apex of the cone. The principle involved in this type of wave shaper is intuitively simple, and results close to the shaper can be predicted directly from geometrical and velocity considerations. The important consideration mentioned above, however, is the fact that wave shapes other than the steady state one, once they are formed, revert rapidly to the steady state and must therefore be applied in the immediate vicinity of the shaper. This is unfortunate from the viewpoint of the total p-t profile, for it is the adverse influence of the shaper on total impulse that causes the sharp reduction in hole volume in shaped-charge applications of this type of wave shape control.

Type 2 wave shapers were first introduced in shaped charges in an effort to achieve the desired wave shape without loss of impulse. The usefulness of this method for wave shaping is strikingly illustrated by the simplified means of obtaining an approximately "plane wave" booster, illustrated in Figure 2. Here the detonation wave in low-density ($\rho_1 \approx 1.05$ g/sec) tetryl (D≈ 5600 m/sec) is passed over a conical cap filled with low-density ($\rho_1 \approx 0.8$ g/sec) TNT (D ≈ 4400 m/sec), converting the wave from a spherical form of relatively low radius of curvature (R/d ≈ 1.5) to an essentially plane wave. The shape of the wave may be adjusted for more accurate shaping in this type of wave shaper simply by careful selection of particle size and/or particle size distribution in the explosive. This influences density and reaction rate, both of which influence velocity. Unfortunately, velocity and detonation pressure are so closely related, through the equation

$$p_2 \approx \rho_1 D W \approx \tfrac{1}{4}\rho_1 D^2 \qquad (1)$$

(p_2 = detonation pressure, ρ_1 = density, D = velocity, W = particle velocity) that flattening (or inversion) of the wave is also accompanied by loss of impulse. In fact, this method may have a more adverse influence on impulse than an inert filler that completely interrupts the wave and requires it to go out around the filler, owing to the fact that p_2 varies as about the 2.5th to 2.8th power of the density, or second power of velocity at constant density (equation 1).

The application of low-order detonation (type 3) in wave shaping has been described by Poulter (Ref 3) and will not be discussed here. However, one must be especially careful to differentiate this type from that described under method 5, in which the detonation wave is interrupted completely for a time τ after which it is re-formed directly as a high-order detonation without an intervening low-order detonation (Refs 4, 5).

Density variations and/or composition variations in a given explosive influence wave shape by their influence on velocity. While this method (type 4) may be used to regulate wave shape, it is in general difficult to control. Figure 3 shows two streak camera traces of detonation waves emerging from cast pentolite with axially reduced densities and/or small axial cavities. Also shown in Figure 3 are two traces of emerging waves from cast 80/20 tritonal and HBX, respectively. In the aluminized explosives it was found that the aluminum tended to concentrate toward the charge axis. Clearly, careful control of the density and composition fluctuations are needed to control wave shape. These both depend primarily on the casting procedure used.

Possibly the most satisfactory and useful method of wave shaping is that of type 5. This type has been used at NOL in the development of "plane wave" boosters (Ref 6) and at ERG in the "cylindrical wave" booster (Ref 7) described in this Symposium by Mr. Ursenbach.

The sympathetic initiation of detonation through various media has been studied extensively as regards limiting thicknesses and the fifty % detonation-failure point. In fact, this constitutes an important means of determining relative sensitivity or "sensitiveness" of explosives. In Reference 5 the time lag in propagation through air, steel, and glass was studied, and it was there shown that, even though the shock wave travels

through the inert medium at velocities near the detonation velocity D, the emerging shock wave alone does not cause detonation in the explosive on the far side of the medium, even for very thin plates. Instead, it merely starts chemical reaction, and by (adiabatic) buildup of temperature, as a result of reaction (and possibly relatively slow thermal conduction through the plate), the temperature again finally reaches the critical level for detonation. (The plate acts effectively as a heat-filter shock-pass.) However, this process involves a time lag τ as a result of the heat-filtering action of the plate. It was shown that τ values for end-on propagation varied nearly directly as the thickness of the inert medium for steel and glass and amounted to as much as 3.4 μsec for plates of about ½-in. diameter thicknesses. For lateral propagation, as in the "cylindrical detonator" much longer time lags have been achieved, namely, up to 20 μsec or more. Following this time lag (τ is calculated as the time between the emergence of the shock wave and the initiation of detonation), the detonation suddenly starts up, usually at high order, although under some conditions it may be "low order." Obviously, this effect is of great importance in wave shaping. The theory of this effect has been discussed more thoroughly in Reference 4. The heat balance equation

$$- \lambda \nabla^2 T + C\rho \frac{\partial T}{\partial t} = \rho Q k' f \qquad (2)$$

(where λ is the conductivity, T the absolute temperature, C the heat capacity, ρ the density, t the time, Q the heat of reaction, k′ the specific rate constant,

$$k' = \frac{kT}{h} e^{\Delta S/R} \; e^{\Delta H^{T}/RT}$$

and f a function determined by the "order" of reaction) may be integrated for the adiabatic case ($\nabla^2 T = 0$) to give (Ref 8)

$$\log \tau = A/T_o + B \qquad (3)$$

where

$$A = \Delta H^{t}/R \text{ and } B = \log \frac{ChRT_o}{Qk'H} e^{-\Delta S^{t}/R}$$

Now if T_0, the initial temperature, is above a certain critical value, nothing external can prevent eventual detonation; reaction will accelerate until detonation finally ensues. In impact, for example, a hot spot may be formed inside the explosive to raise the temperature to T_0. The chemical reaction will then commence at the rate corresponding to T_0, but since explosives in general react exothermally, T will build up in adiabatic decomposition and thus cause the reaction rate to increase via a "vicious cycle." The primary condition for (effective) adiabatic decomposition is simply that heat is generated by reaction much faster than it can be lost by conduction, radiation, or convection. This will nearly always be the case if T_0 is appreciably above the so-called "explosion temperature" (200-400°C).

Now the shock wave alone, on passing from the detonation front into an inert medium, can raise the temperature in a solid usually only to a relatively small fraction (say, 20 - 40%) of the detonation temperature. Since chemical reaction rate depends critically on T, this is (perhaps always) insufficient to cause detonation directly; only when accompanied by a "heat pulse" sufficient to raise T to or near T_s can detonation continue uninterrupted on the opposite side of the plate or inert medium. If T is lower than this, but not sufficiently lower that re-formation is not possible following adiabatic buildup of T, detonation will re-form after the time given by equation (3). The magnitude of r (or T_0) can be estimated for any initial temperature T_0 (or r), and entropies of activation (cf. Reference 8). The following data were computed for some primary explosives.

	$r = 50\ \mu$sec	$r = 500\ \mu$sec
Mercury fulminate	825°K ($= T_0$)	710°K
Lead azide	930	820
Lead styphnate	770	725

Since A and B will not be greatly different for different explosives, it is seen from these results that a time lag of 3 - 4 μsec means an initial temperature T_0 of about 1000°K. This, in fact, is the temperature one computes for a shock wave (without an accompanying "heat pulse") in solids from the compressibilities and entropy effects associated with shocks (Ref 9). In other words, shocks do not have an accompanying "heat pulse," other than that associated with dynamic compression, but

"detonation shocks" apparently do (Ref 4). If this were not the case, it would not seem possible to interrupt detonation for a controlled period of time τ by means of glass and steel plates of thicknesses up to about ½ charge diameter.

This τ-time wave interruption method in wave shaping was applied in this laboratory in shaped-charge investigations where it was shown that one may shape the wave front (Fig 4) to increase the penetration by as much as 30% without loss (indeed with slight increases) of hole volume (Ref 2). Its most important application in this laboratory, however, has been the "cylindrical wave" detonator.

SHAPING OF PRESSURE-TIME PULSE

In unconfined cylindrical charges of solid (and presumably also liquid) explosives a "detonation head" of shape corresponding to spherical cones develops (see illustrations of Fig ii, Reference 10) during propagation of the wave front over a length L of about 3-4 charge diameters. In the region L < 3d to 4d, this (theoretical) detonation head in an ideal explosive, of small reaction zone length, is shaped as successive truncated spherical cones of height proportional to length of charge, and for $L \geq 4d$ it propagates in steady state as a constant, solid cone of height about one charge diameter, and with a spherically shaped front having a radius of curvature of about 3.5 d. Under maximum confinement (at L/d > 4) this head is somewhat different; it is perhaps best represented by a cylinder of height about (⅔)d, on the end of which is placed a cone of height d making a total "head" of volume about twice as great as in the unconfined case. While one may shape the front of this head to be "plane", or with any other desired shape, it is clear that a flat plate of constant thickness will not remain flat if impacted by a (plane wave front) detonation head, unless the "head" is changed in some way from this conical form to a cylindrical form. One can, however, compensate for the conical form of the detonation head in several ways such as to prevent tensions from fracturing the plate after it has been impulsively loaded by the conical detonation head. The plate may be a conical one with its base in contact with the explosive and apex foremost, such that its thickness is everywhere proportional to that of the detonation head, and upon impact by the "head" each element of the plate

should then move out at the same speed. One can also prevent tensions from developing in a plate of constant thickness by shaping it initially as a re-entrant cone of suitable cone angle that it eventually becomes a flat plate, after it has absorbed all possible momentum from the detonation head. This projectile will then undergo merely compression during impact loading and will not fragment. Pugh and later Rinehart (Ref 11) applied this technique in generating a very-high-velocity single particle, and similar techniques are being used in the author's laboratory at present to study target penetration by high-velocity impact.

The problem of "shaping" the pressure-time pulse is most critical with the smallest or thinnest targets. As the thickness is increased, the impulse from the detonation head spreads out more and more across the whole target. Clay, Keyes, and Cook (Ref 12) have discussed the theory of integrated impulse loading of flat plates by the detonation head developed in cylindrical charges. They show that this process may be treated with surprisingly good accuracy by the theory of the "billiard ball," if the target has a mass not appreciably greater than the total mass of the detonation head. If, however, the target mass is appreciably greater than this, the impulse absorbed by the target will be appreciably greater than that imparted to the target from the detonation head. This is because the gases may continue to apply pressure on the heavy (slowly moving) target long after the detonation head pulse has expended itself against the target. This consideration is of great importance in the "continuous rod" warhead developed at New Mexico School of Mines by Mr. M. L. Kempton and coworkers. The importance of the p-t curve is perhaps best illustrated by the results of application of the cylindrical initiator in this warhead obtained in recent tests conducted jointly by ERG and NMSM. Since these results are of great interest in the application of wave shaping in impact loading of targets they will be discussed briefly here.

The "cylindrical initiator" develops a detonation head in a cylindrical charge having a shape such as that illustrated in Figure 5a. This "detonation head" (upon reaching the periphery of the charge, as illustrated in Fig 5a) would be a cylindrical "pipe" of thickness about 0.35 R to 0.4 R (where R is the radius of the cylindrical charge) except for end effects. The end effects will cause the detonation head from the cylindrical charge to taper off from about 0.35 R to zero, starting at a distance

about ½ R from each end of the charge (See Fig 5a).

Now if the mass of the rods M_p were not too much greater than the mass of this detonation head M_h, the rods would acquire a final velocity V_p given by

$$V_p = 2\bar{W}M_h/(M_h + M_p) \quad (4)$$

These rods would then acquire the maximum kinetic energy $\frac{1}{2} M_p V_p^2$ for the mass $M_p = M_h$. But since the ends of the rod would accelerate more slowly at first than the part within the region of the "head" of constant thickness, that part of the rod would go into tension. If this tension is sufficient, the rods should then fragment at a position about ½ R from each end. If, however, this tension were insufficient for fragmentation, the whole rod would acquire the shape shown in Figure 5b.

In the continuous rod warheads studied, the rods were much heavier than M_h. Hence in this case it was possible to continue applying pressure on the rods a relatively long time after delivering the total detonation head impulse to the rods. But owing to end effects, this pressure was applied for a much longer time at the center than toward the ends. While the final velocity was considerably (about 30%) higher than that given by equation (4), the rods went quickly into a V shape and either broke at the center or continued into the shape illustrated in Figure 5c (right hand side). The initial shaping of the rod to conform with the detonation head could, however, easily be seen by the hook on the end of each rod, as illustrated in Figure 5c. (It should be a simple matter, however, to match the load with the p-t profile by proper adjustment of rod thickness using tapered rods. While this may not have practical value, it does have considerable theoretical value.)

It has been amply demonstrated (Ref 12) that the targets attain a maximum possible kinetic energy if $M_p = M_h$. Under conditions in which the kinetic energy is the important criterion for damage, therefore, one should use this mass for the target. In shaped charges this is the criterion for optimum hole volume; maximum depth frequently (but not

always) corresponds to this condition. However, in fragmentation bombs, continuous rod warheads, and similar applications, one must select a load of mass greater than M_h because the damage criterion then involves a compromise between total kinetic energy and total impulse.

Apparently very little thought has as yet been given to the problem of "impulse" shaping. It is evident, however, from the meager information available, such as is illustrated by the above examples, that both wave front and impulse or pressure-time shaping are of great importance in impulse loading of targets by explosive attack. If this article has brought this problem into focus it has served an important objective.

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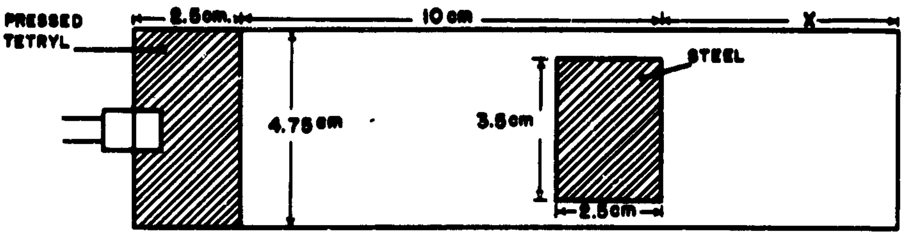
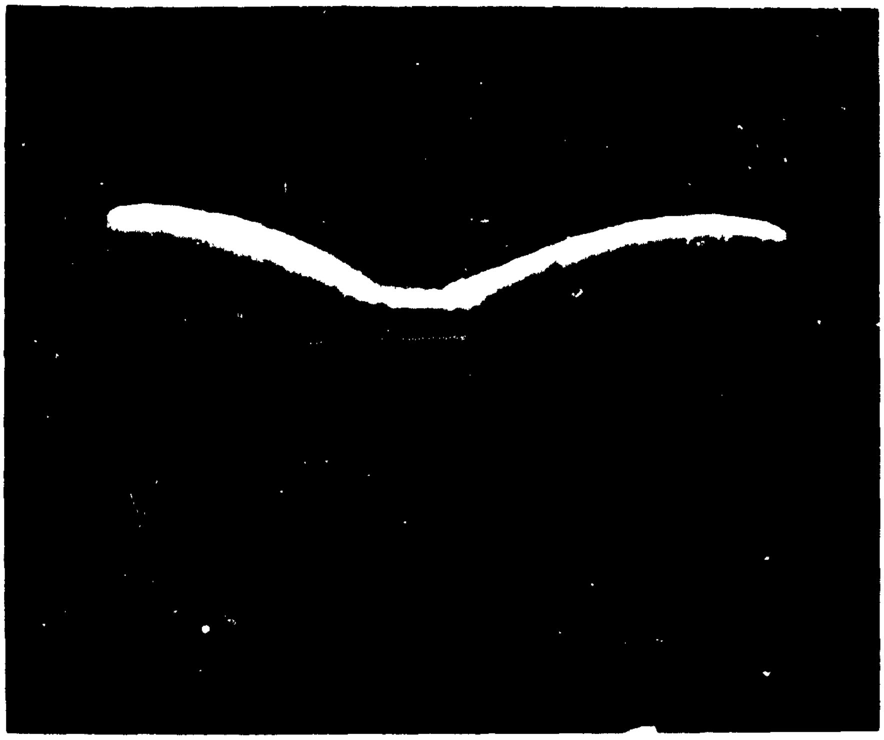


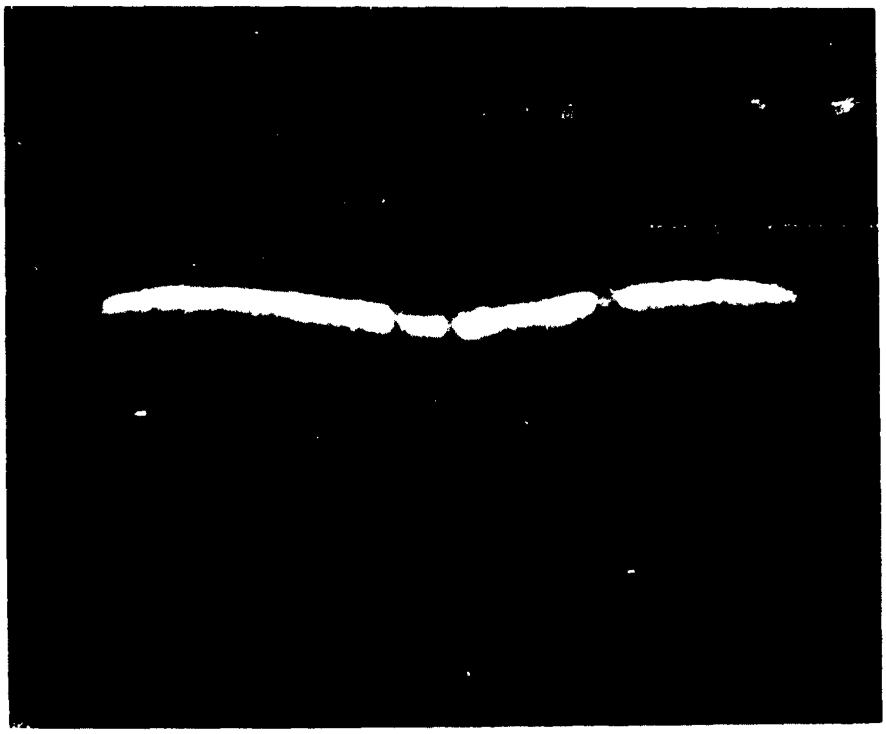
a. Assembly

b. Trace for x = 1.0 cm

Fig 1 Wave Shape with Interrupter-Type Filler

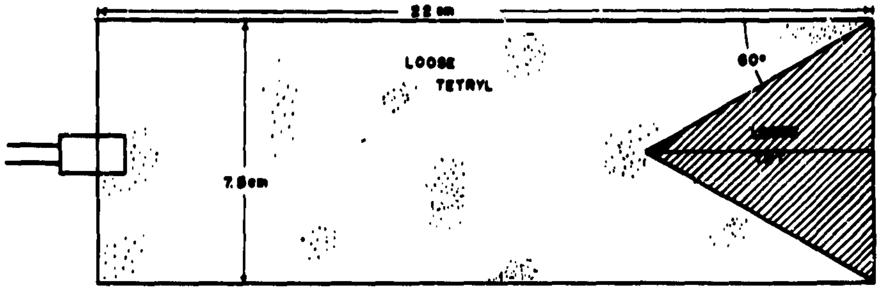


c. Trace for x = 3 cm

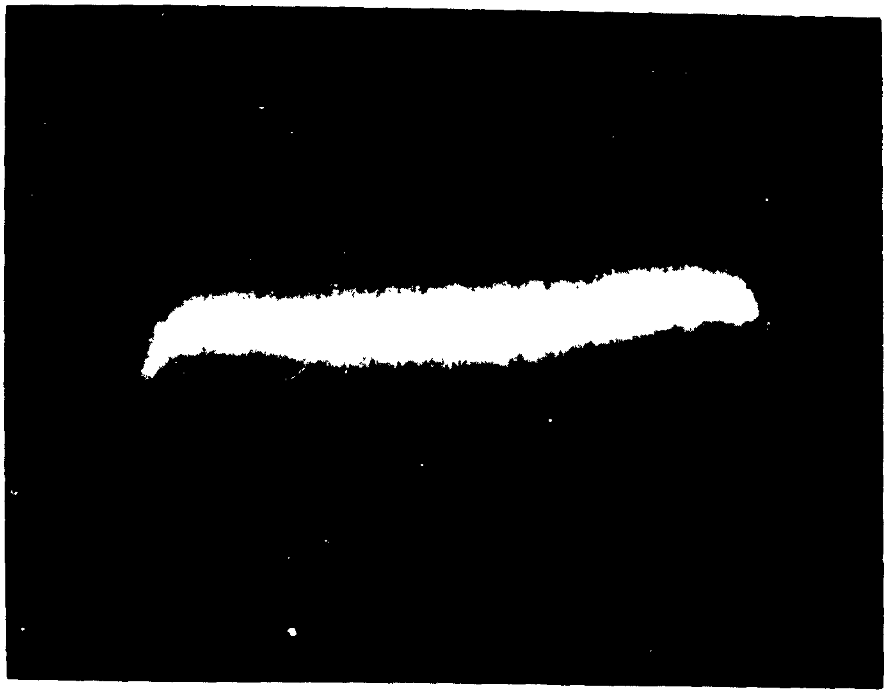


d. Trace for x = 5 cm

Fig 1 Wave Shape with Interrupter-Type Filler (Cont.)



a. Assembly



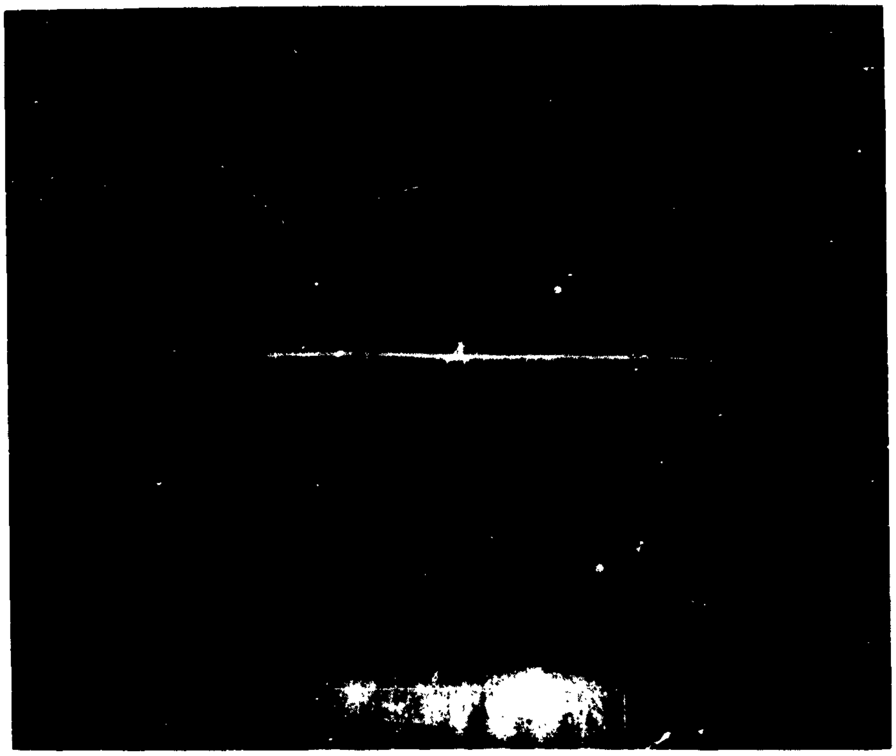
b. Trace Showing Wave Shape

Fig 2 Simple "Plane Wave" Booster

a. Wave Shape Traces of Emergent Wave from 50/50 Cast Pentolite with Reduced Axial Density

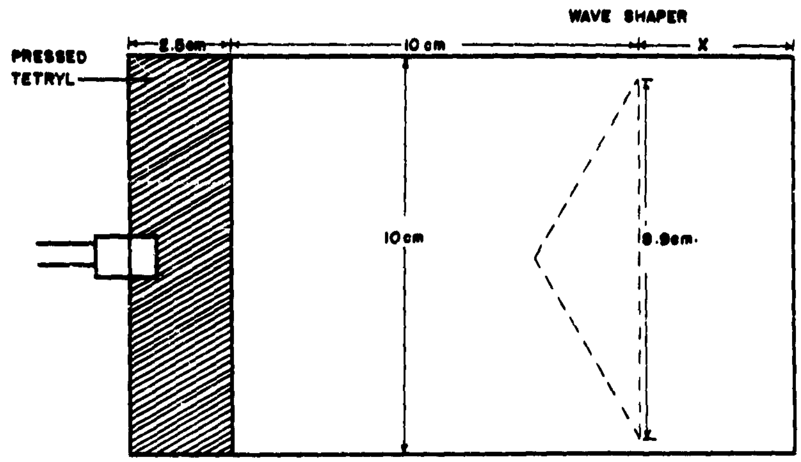
b. Wave Shape Trace for 80/20 Tritonal with Slight Al Concentration along Central Axis

Fig 3 Wave Shape for Non-Uniform Charges

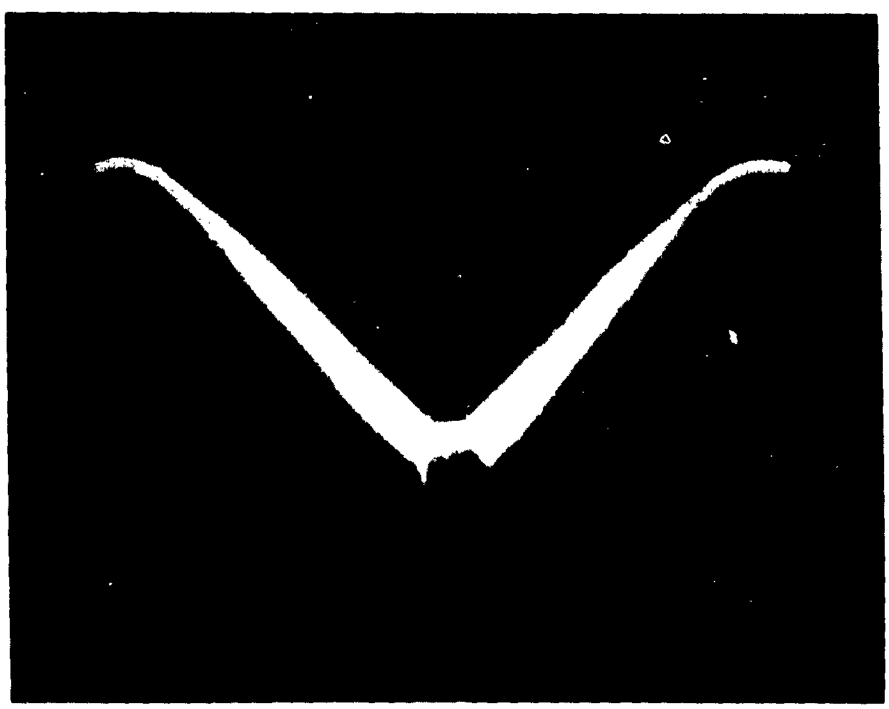


c. Wave Shape Trace for HBX with Slight Al Concentration along Central Axis

Fig 3 Wave Shape for Non-Uniform Charges (Cont.)

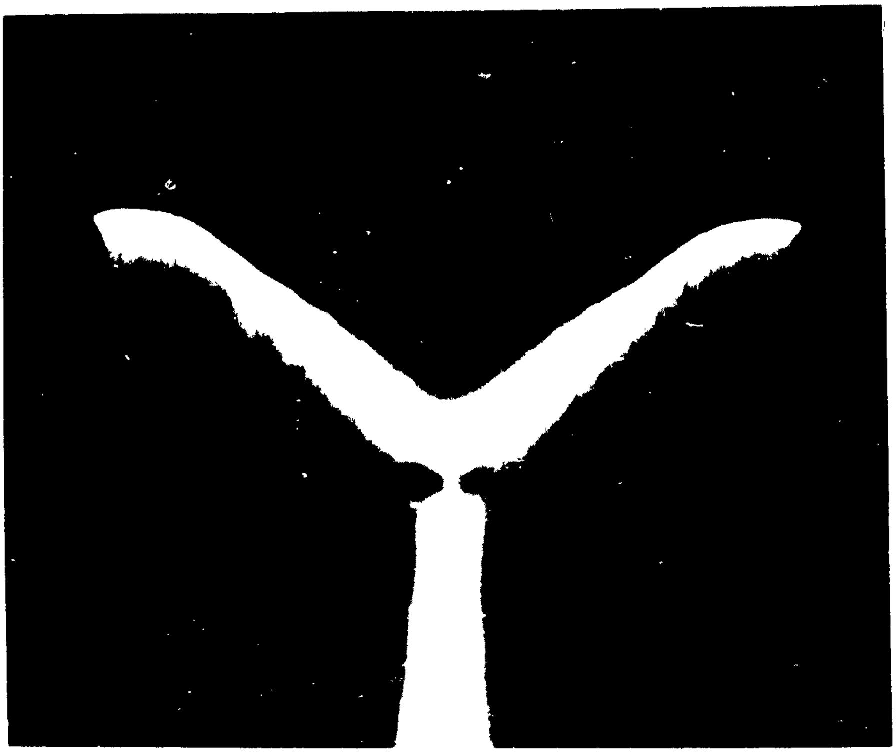


a. Assembly

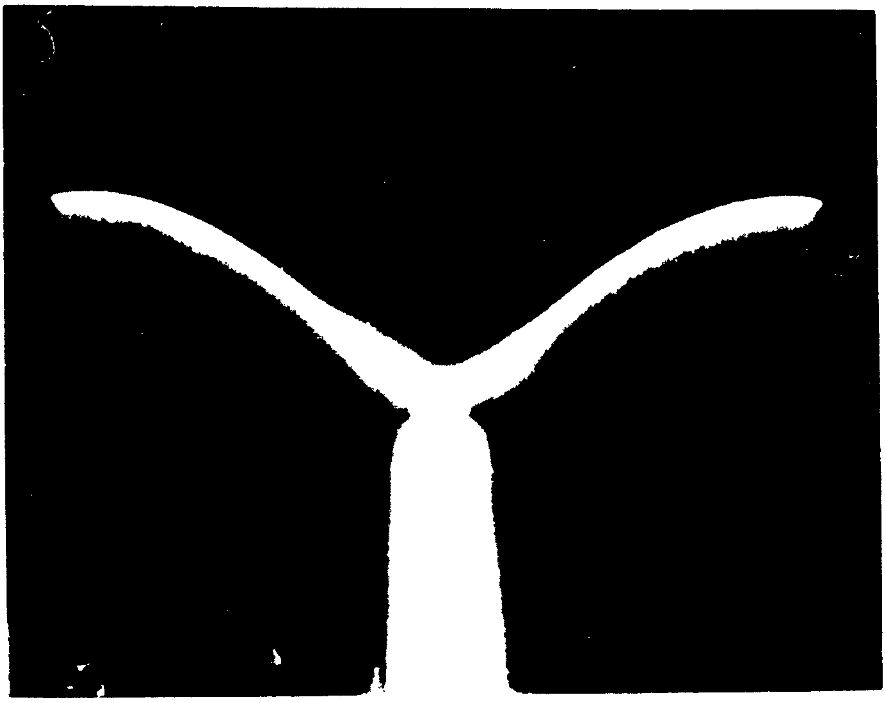


b. $x = 1.1$ cm

Fig 4 Wave Shapes from Conical Steel and Glass Fillers

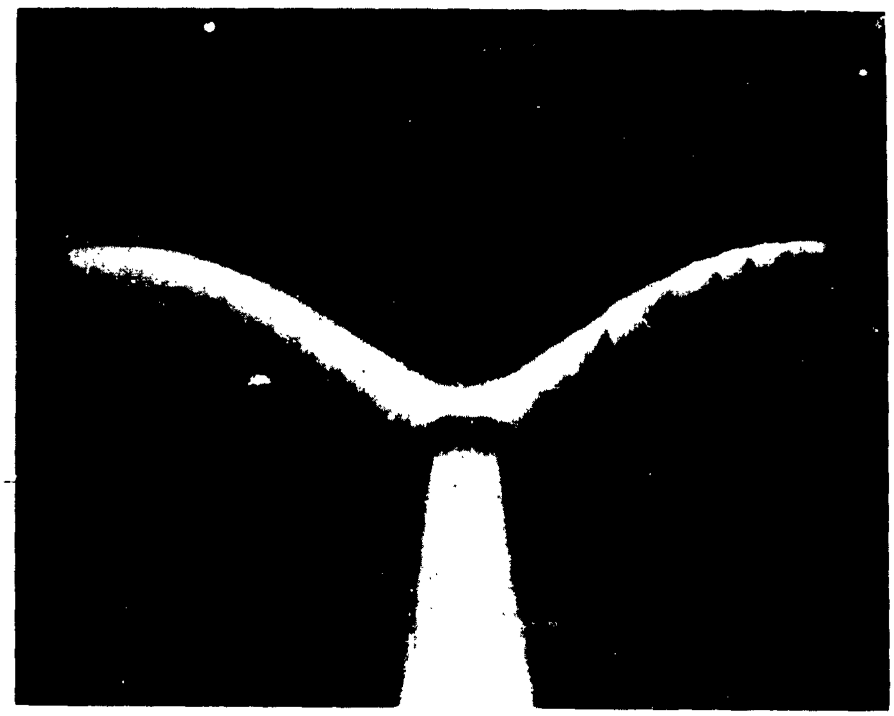


c. x = 2.0 cm



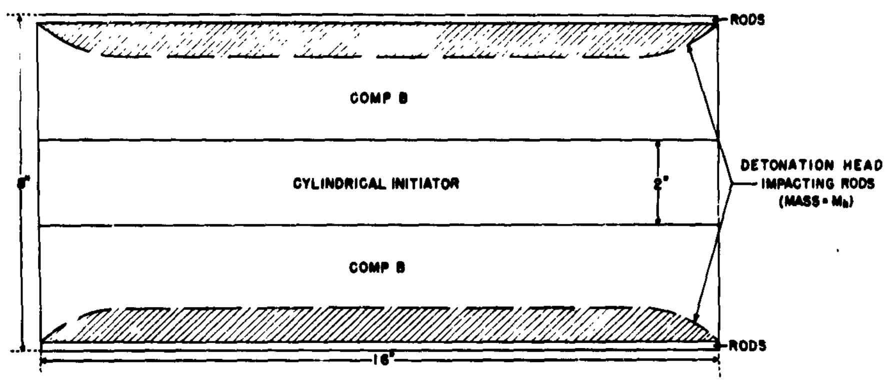
d. x = 3.9 cm

Fig 4 Wave Shapes from Conical Steel and Glass Fillers (Cont.)

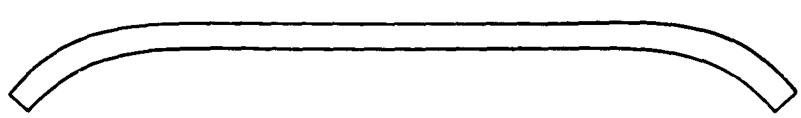


e. x = 5.0 cm

Fig 4 Wave Shapes from Conical Steel and Glass Fillers (Cont.)

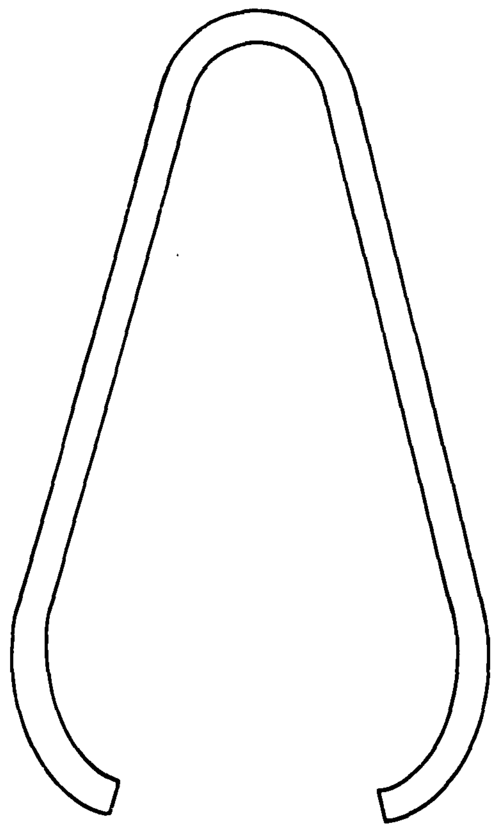


a. Cross-section of Rod Warhead



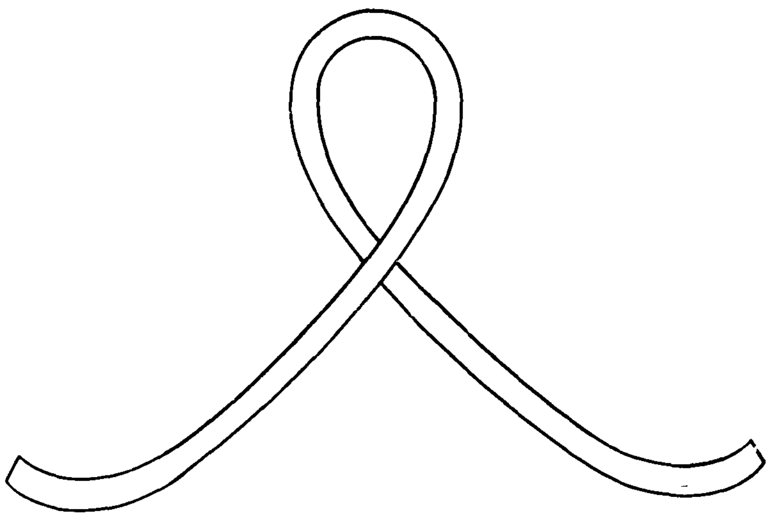
b. Predicted Shape of Rod at Several Feet from Point of Detonation for Rods of $M \leq M_h$

Fig 5 Application of Cylindrical Initiator in "Continuous Rod" Warhead



c. Actual Shape of Rods at Several Feet from Point of Detonation for Rods of $M >> M_h$ (at short distance)

Fig 5 Application of Cylindrical Initiator in "Continuous Rod" Warhead (Cont.)



d. Actual Shape of Rods at Several Feet from Point of Detonation for Rods of $M >> M_h$ (at longer distance)

Fig 5 Application of Cylindrical Initiator in "Continuous Rod" Warhead (Cont.)

MECHANISM OF WAVE SHAPING TECHNIQUES

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INTRODUCTION

It has only been during the past few years that the importance of wave shaping or detonation front shaping has been recognized as having any real application in the field of ordinary munitions. While I would not like to minimize in any way the importance of detonation front shaping, I would at the same time like to emphasize the fact that of perhaps even more importance in many cases is the impulse distribution across the detonation front.

To illustrate what I mean, suppose we want to accelerate a flat steel disc normal to its surface by means of an explosive charge such as shown in Figure 1. If we place it on the end of a cylindrical charge of

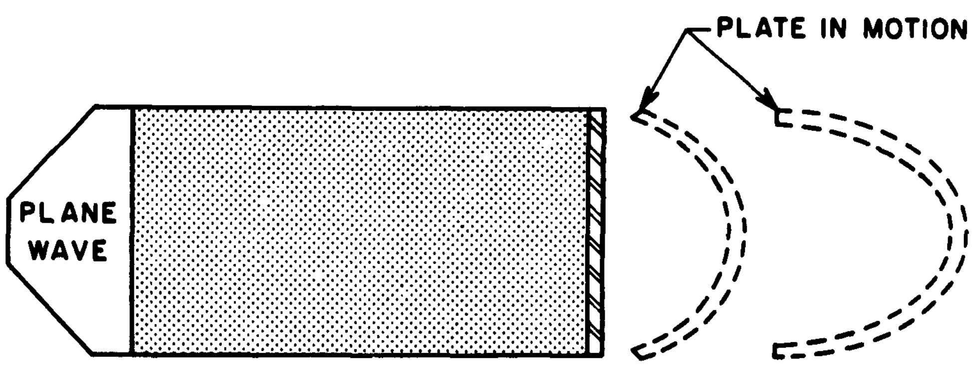


Fig 1 Deformation of Plate

the same diameter and detonate this charge by means of a plane wave, the central portion of the plate would advance far more rapidly than the edge because of the much greater impulse at the center of the charge due to its greater confinement. If we examine the development of the relief wave in a cylindrical charge (Fig 2) it becomes apparent that this

should be the case. The relief wave envelope develops from a thin, uniform-thickness disc to a cone whose height-to-diameter ratio depends upon the relative velocity of the detonation front and the relief wave velocity. The full conical relief wave envelope develops after the detonation front has traveled about 2½ to 3 charge diameters and is independent of the manner in which the charge was detonated.

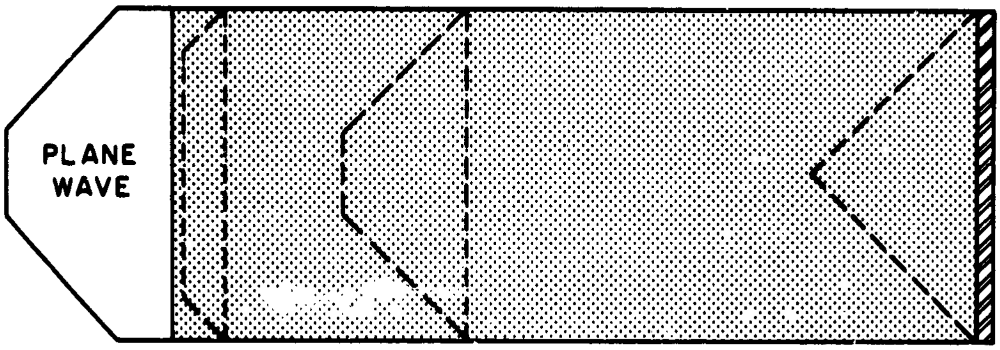


Fig 2 Development of Relief Wave

Having raised a word of caution relative to the importance of impulses, we will proceed with a discussion of the various methods of developing a desired detonation front and return later to the effect of the impulse.

DISCUSSION

Detonation Rate

At this point it might be well to state a physical definition of a detonation pulse and detonation velocity. A normal shock pulse traveling in an inert medium is continually doing work on the medium through which it is traveling, and hence it is continually being attenuated and therefore decelerated. A detonation is a true shock pulse but one in which the energy being lost in attenuation is being replaced by the energy being released by the chemical reaction associated with the detonation process.

The detonation velocity of an explosive is therefore the velocity of a

plane shock pulse in the explosive through which it is traveling and in which the attenuation is just compensated for by the energy which it receives from the chemical reaction. Consequently anything which tends to increase the attenuation will tend to decrease the detonation rate and, conversely, anything which tends to increase the energy received by the detonation pulse will increase the detonation rate.

An increase in mass per unit volume of the explosive without a corresponding increase in energy released will decrease the detonation rate, and vice-versa.

An increase or decrease in mass of explosive being swept out by a detonation front may be accomplished by a change in the density of the explosive due to loading with inert material or by making the detonation front convex or concave.

Effect of Curvature of the Detonation Front Upon Detonation Rate

The detonation rate is a function not only of the curvature of the detonation front but of its previous history as well. For example, the detonation rate of a spherical concave detonation front or implosion whose radius of curvature is, say, 10 cm would have a different detonation rate if it were initiated at a radius of curvature of 15 cm than it would if it were initiated at a radius of curvature of 20 cm. For a completely spherical implosion the detonation rate is some inverse function of the radius of curvature plus some direct function of the convergence that the detonation front has experienced since it was initiated.

The direct effect of curvature upon the detonation rate is comparatively small until the radius of curvature becomes rather small. However, since the detonation pressure is a direct function of the square of the detonation rate, comparatively small changes in rate may produce an appreciable effect. The direct effect of the curvature upon the detonation front can be calculated from the approximate equation

$$V_R = V_\infty \; e^{4.78/R}$$

where V_∞ is the detonation rate of a plane detonation front and V_R is the detonation rate of a concave spherical detonation front whose radius of curvature is R in millimeters. A few typical values are shown in Table 1.

TABLE 1

Effect of Curvature on Detonation Rate

R (mm)	V_R (mm/μsec)
3	38.9
6	17.5
12	11.8
25.4 (1 in.)	10.9
30	9.3
50.8 (2 in.)	8.7
60	8.6
76.5 (3 in.)	8.4
101.6 (4 in.)	8.3
127 (5 in.)	8.2
∞	7.91

However, there is superimposed upon this an effect due to the convergence which the detonation front has experienced prior to its reaching the value R. Since the direct effect of curvature upon the detonation rate is so small until the curvature becomes quite small, the effect of the convergence which it has experienced in the past is probably a second-order effect.

If we now consider other than a symmetrical implosion, the situation becomes more complicated since one must use the equivalent spherical radius of curvature where

$$\frac{2}{R} = \frac{1}{r_1} + \frac{1}{r_2} .$$

In the special cases of cylindrical or conical detonation fronts since $r_1 = \infty$, $R = 2r_2$.

Optical Method of Wave Shaping

One may look at the problem of detonation front shaping strictly from the standpoint of optics, in which case it becomes merely a matter of selecting a combination of path length and detonation rate to convert some comparatively simple and easy to generate detonation front to the desired geodesic surface.

Strange as it may seem, one of the most difficult detonation fronts to develop is a completely spherical convex or expanding detonation front. This is because most primary detonation initiation devices initiate a detonation traveling in one direction.

Normal point initiation develops a detonation front which develops into a section of a sphere, and this is the most common starting point from which to develop other desired detonation fronts.

Explosives of different detonation rates can therefore be used to change the shape of the detonation front just as materials of different index of refraction are used in optics. Also, just as in optics, the Huygens' principle can be used to generate the new detonation front in such charges as that shown in Figure 3.

Another commonly used technique is to place a shell of high detonation rate explosive over a cone of lower detonation rate, as in Figure 4, in which the angle of the cone is such that the high-rate explosive detonates along the slant height of the cone while the lower detonation rate explosive forming the cone detonates from its apex to its base, thus developing a plane detonation front.

The detonation rate of conventional high explosives can be varied over a rather large range by mixing explosives of different detonation rates or mixing a non-explosive with an explosive. At least three types of materials are used for this purpose. These are discussed in the following paragraphs.

1. The first type of material is one which is not intended to change the attenuation but merely reduces the energy released per unit mass of

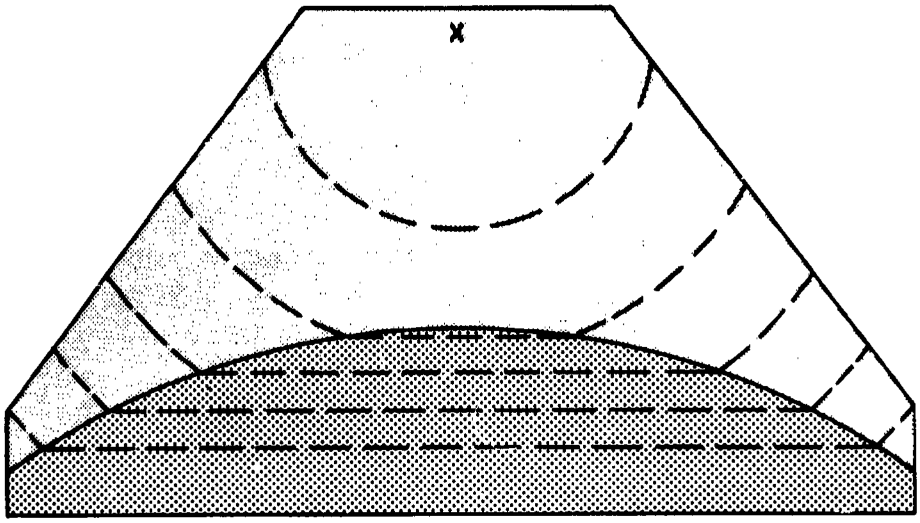


Fig 3 Application of Huygens' Principle

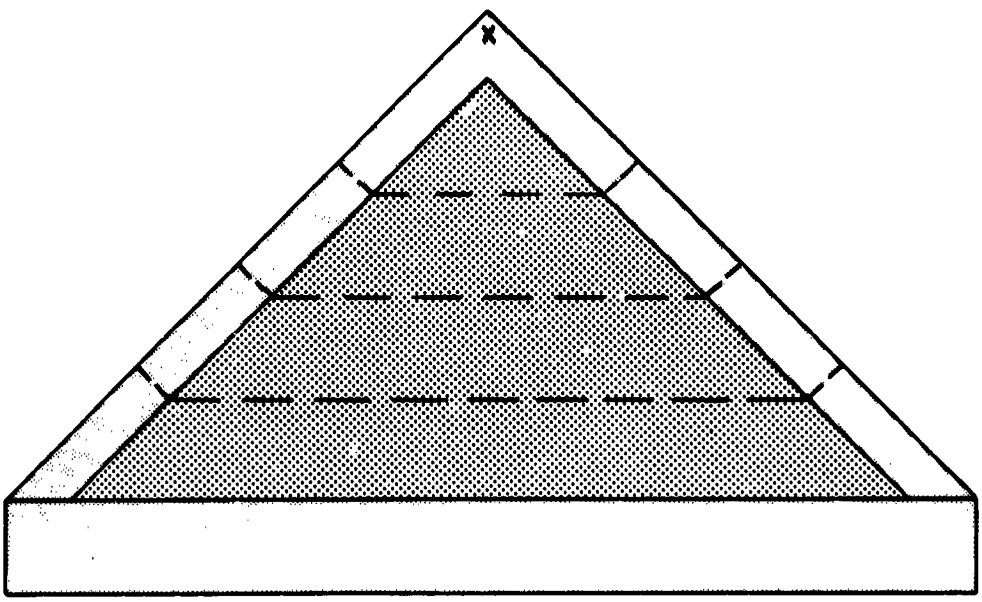


Fig 4 Combination of Explosives of Different Detonation Rates

the mixture. Sodium chloride and graphite, both of which are compatible with most explosives, are examples of this kind of material.

a. Sodium chloride/TNT mixtures containing as little as 35% TNT will detonate uniformly and the detonation rate is reduced to 80% that of solid TNT, with the decrease in detonation rate being directly proportional to the percent of salt added.

b. Graphite in RDX also provides a good mixture for reducing the detonation rate, and again the reduction in detonation rate is proportional to the percent of graphite in the mixture.

c. Salt in the plastic explosive C-3 will make it detonate uniformly with as little as 30% of C-3 in the mixture and with a detonation rate reduced to only 58% of its former value.

Curves for these three mixtures are shown in Figure 5, from which it will be seen that the salt and C-3 mixture does not give a straight line. This curve should be rechecked in that its shape may indicate that during the process of mechanical mixing the particle size of the salt in the high percent salt mixtures may have been changed and be a contributing factor. A great variety of other materials will doubtless work equally well.

2. Other types of inert materials used are metallic powders, particularly very dense ones such as tungsten. In this case a comparatively small quantity of metal powder on a volume basis produces a very large change in density and hence an appreciable change in rate. No curves are available for these materials.

3. A third type of material is commonly mixed with oxygen-deficient explosives, which include most of the military-type high explosives includes some of the nitrate salts or other oxidizing agents in order to provide additional oxygen. These may be nitrates of high- or low-density metals depending on whether it is desired to increase the density of the mixture or keep it as low as possible.

There are two kinds of the optical type explosive lenses which take advantage of the difference in detonation rate of the explosives. In one the front face of the lens is composed of the explosive having the lower

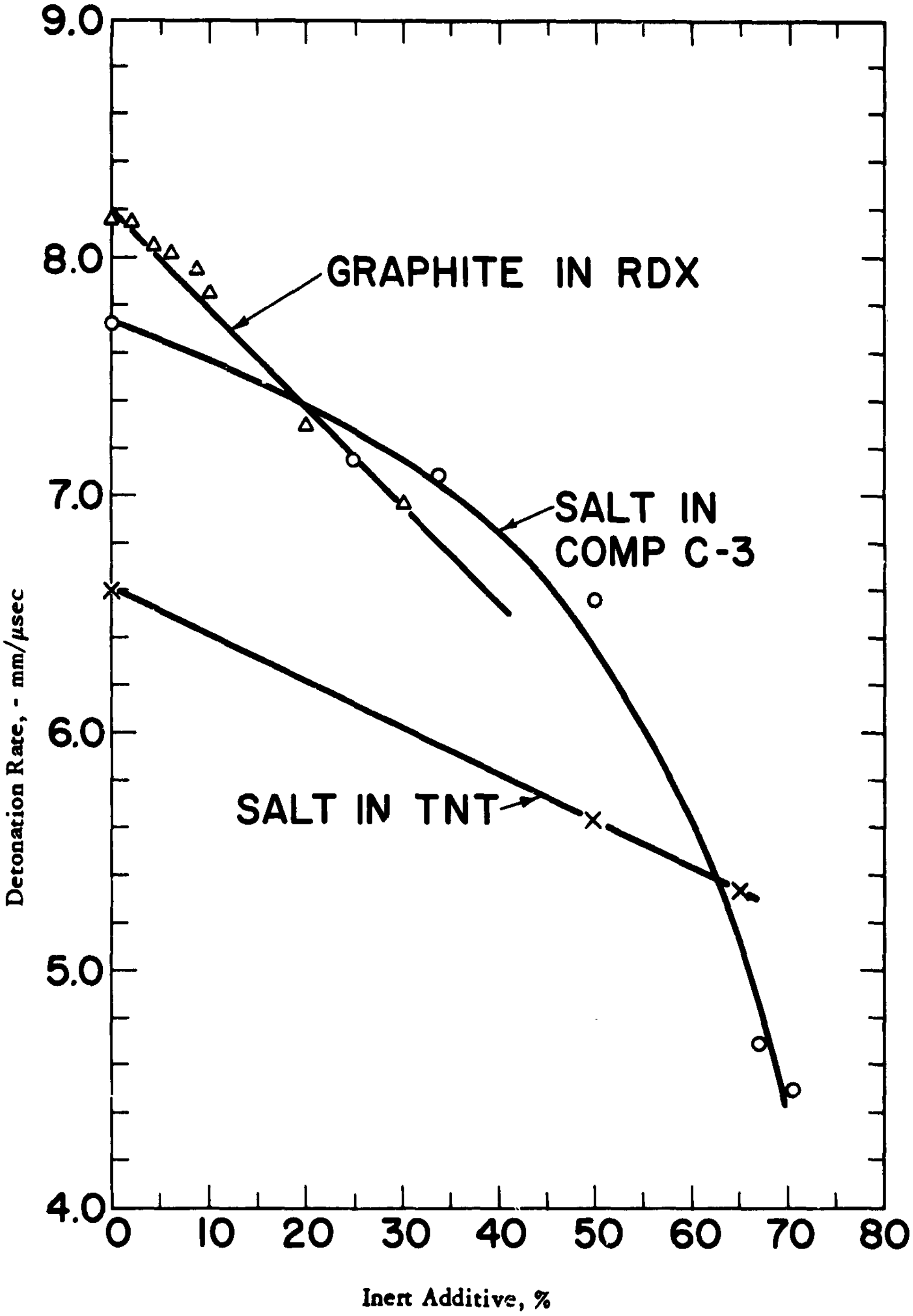


Fig 5 Measured Detonation Velocities of Explosives with Inert Additives

detonation rate (Fig 3) and in the other (Fig 6) the face of the lens is formed on the higher detonation rate explosive.

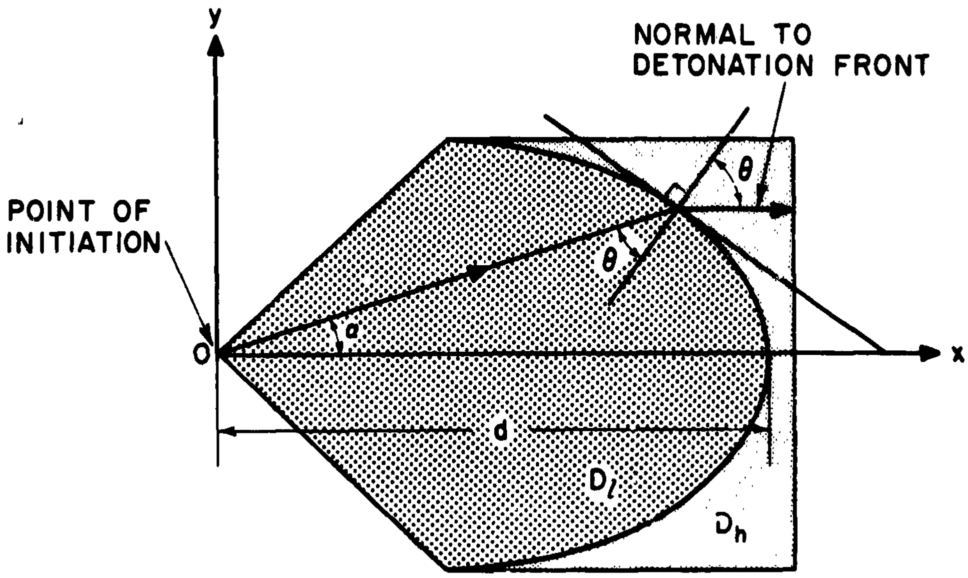


Fig 6 Optical Type Explosive Lens

Air Lenses

Another very effective means of shaping the detonation front is merely to introduce a variable time delay over different portions of the detonation front. This can be done very effectively by introducing an air gap across which some material, usually a metal plate, must travel and strike the explosive on the opposite side of the air gap with sufficient velocity to initiate detonation. It is possible by this technique to introduce relatively large time delays. The plane wave developed by Dr. Jacobs at NOL is a good example of this type of lens. A very simple air lens in which it is desired to develop a concave spherical section detonation front is shown in Figure 7.

There is a great variety of such lenses and, if the delay time required at various points is known the thickness of the traveling plate and the thickness of the air gap can be adjusted to develop a great variety of wave shapes. It is possible by this technique to use air gaps of several

centimeters and, hence, get time delays in excess of 25 to 50 μsec. By means of one flat metal plate and one very wide angle metal plate it is possible to develop a plane wave which does not have the big disadvantage inherent in most plane waves, that is, that the impulse in this plane wave is nearly uniform throughout its entire area.

In the case of the plane wave generator, such as is shown in Figure 4, this central cone of low detonation rate explosive can be replaced by an inert material which will transmit a strong shock pulse without too much attenuation. One material which has been successfully used in this manner is aluminum, or aluminum alloy. Aluminum is particularly good in that it has a comparatively low attenuation of only 15% per inch of travel of a plane shock pulse.

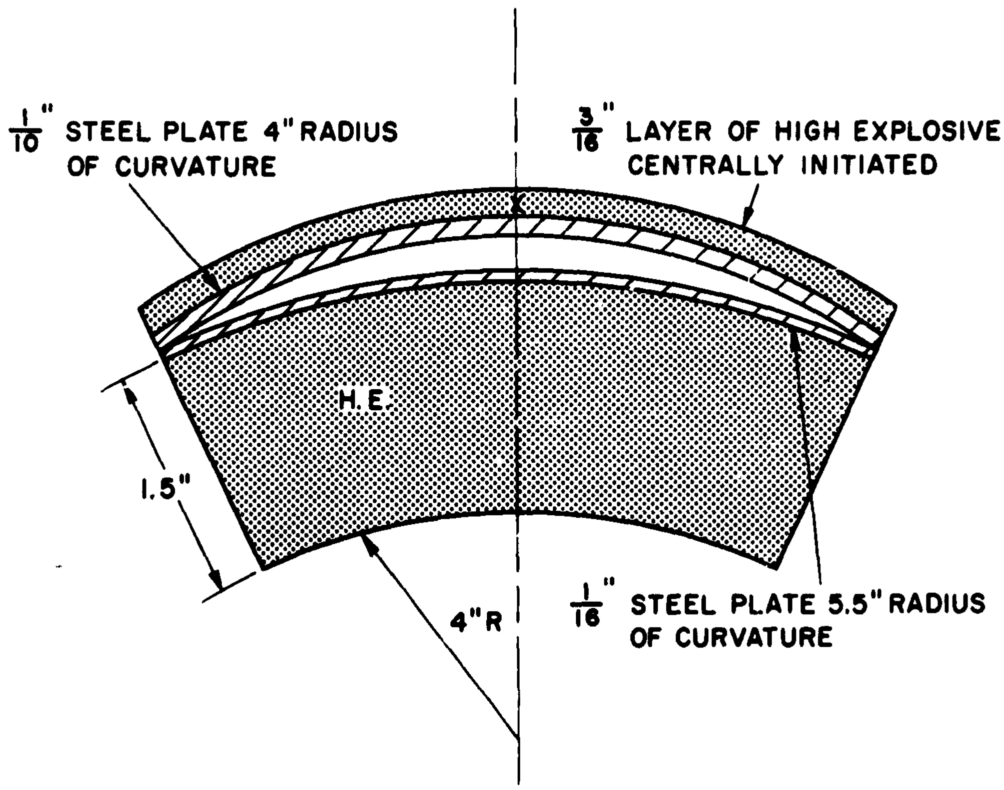


Fig 7 Simple Air Lens

If one knows the percent attenuation of a shock pulse per inch of travel in a medium, the equivalent spherical radius of curvature of a concave shock front in which the convergence will just equal the attenuation turns out to be a very simple relation: three divided by the percent attenuation equals the spherical radius of curvature in inches.

Since the attenuation of a plane shock pulse in aluminum is 15% per inch of travel, $R = 3/0.15 = 20$ inches. For an 80-degree cone the equivalent spherical radius of curvature R of the surface of the cone adjacent to the base is $2/R = 1/\infty + 1/r_2$ or $R = 2r_2$. Since R for aluminum is 20 inches, $r_2 = 10$ inches.

The diameter of the base of an 80-degree aluminum cone in which the convergence at the surface adjacent to the base will just compensate for the attenuation is $2r_2 \sin 10° = 15.32$ inches. However, since the full detonation pressure is not required to initiate detonation, it is probable that such a plane wave would work satisfactorily even though it were appreciably iarger than 15.32 inches. In any case, this provides a technique for making a rather large plane wave generator using a comparatively small quantity of high explosive.

Although no plane generators of this type as large as 15 inches in diameter have been fired, Dr. Katz of Poulter Laboratories has developed precision aluminum-cone plane-wave generators up to 6 inches, and this work is continuing to increasing diameters.

One type of initiation for which there is frequent use, particularly in research in this field, is a linear detonation. Dr. Erkman of our Laboratories has developed such a charge in which one can initiate an explosive charge along a straight line simultaneously from a point initiation. The Erkman lens (Fig 8) consists simply of deforming a sheet of explosive normal to its surface to such an extent that the detonation travel path from the point of initiation to all points along a straight line is the same. Such a lens makes possible, or at least simplifies, many studies which would be complicated by the curvature of the detonation front of a sheet of explosive. Figure 8 is a photograph of the platic form oven which the triangular sheet of explosive is placed.

A combination of the Erkman lens and an air wedge lens again makes

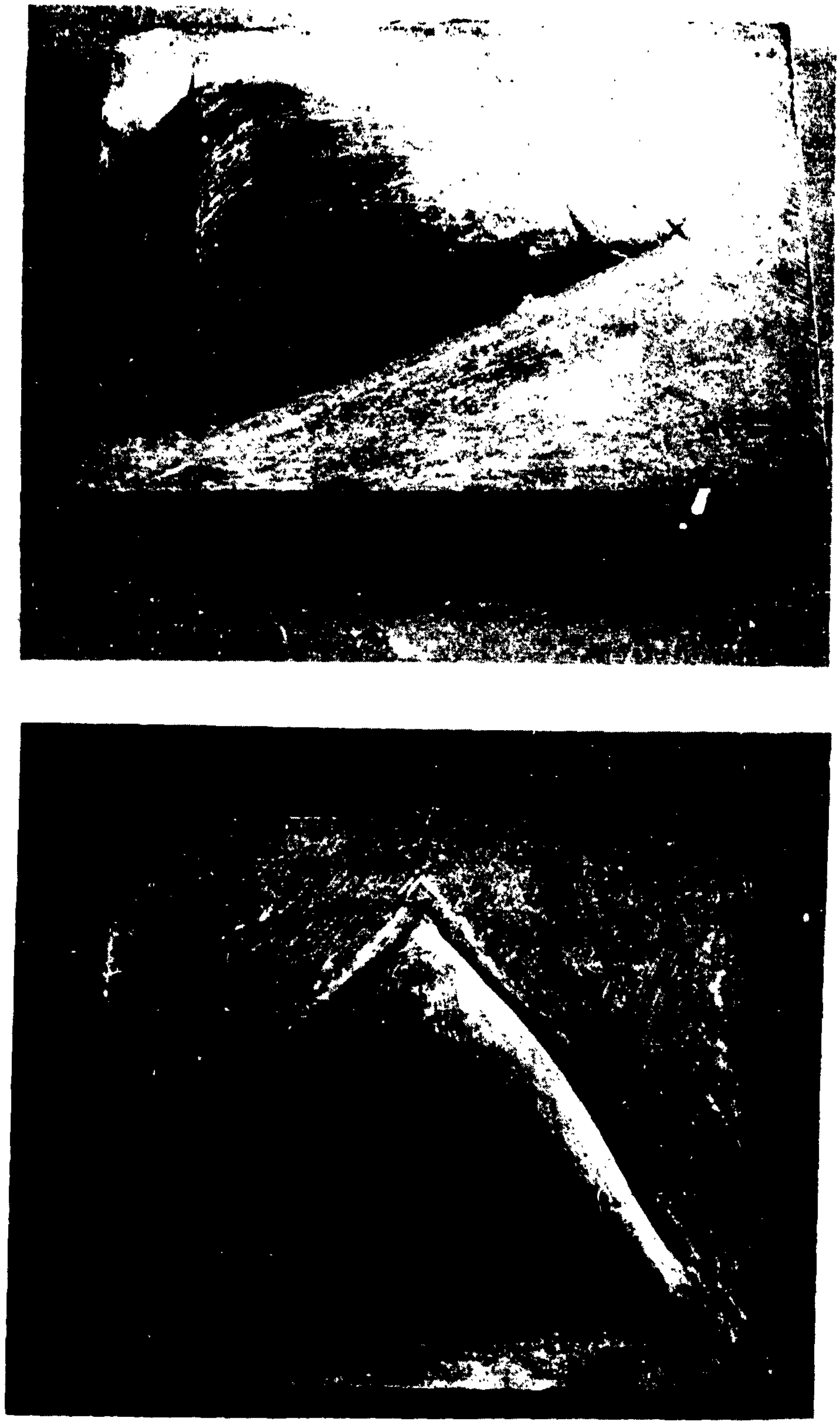


Fig 8 Plaster Form for Explosive Sheet

it possible to develop a plane wave with a completely uniform impulse throughout except, of course, for a small edge effect. If such a plane wave is made up with a 3/8-inch-thick layer of HE driving a 1/8-inch-thick plate of aluminum against an explosive charge, the aluminum plate should make an angle of 14.5 degrees with the surface of the HE which it is intended to initiate. By varying this angle it becomes possible to progressively initiate an explosive charge across its surface at any desired rate which is higher than the detonation rate of the HE being used. Such an arrangement becomes very useful in studying such things as the effect of the angle at which a detonation front strikes the explosive metal interface upon the velocity and direction imparted to the metal plate.

Another modification of this type of lens is shown in Figure 9. A plane wave which will give a uniform impulse throughout is essential in any explosive system where it is desired to study a unidirectional effect.

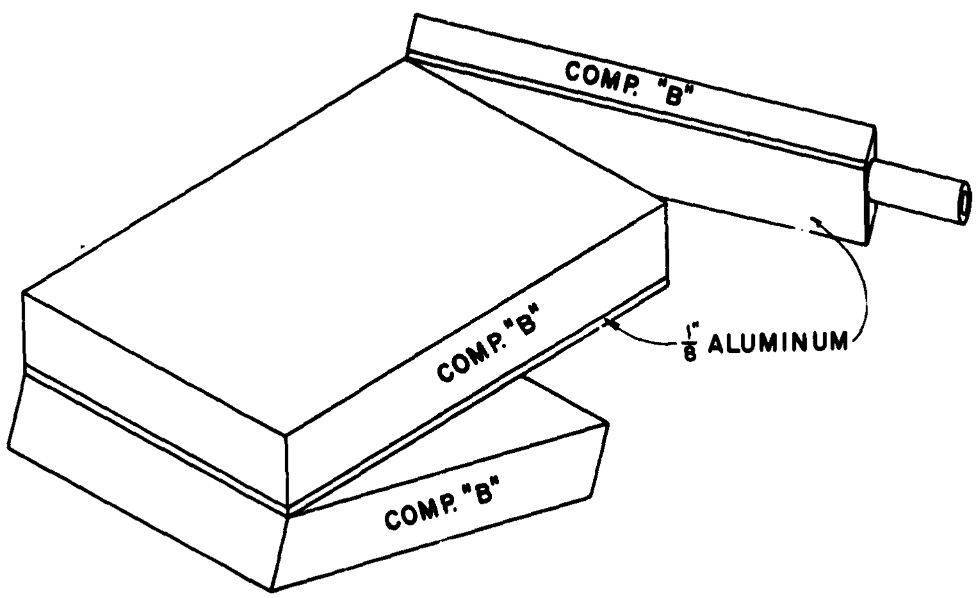


Fig 9 Combination of Erkman Lens and Air Lens

The Selection of Metals for Use in Wave Shaping

There are many applications of wave shaping in which it is impractical to use an air lens because of the acceleration or deceleration that the munition must withstand. In such cases it is desirable to select a material which will have a low shock velocity to obtain the desired time delay, but at the same time will have a high particle velocity in order to initiate the explosive more effectively after traversing the time delay gap.

In order to obtain these physical properties the material must have as high a density as possible consistent with having a large compressibility. Two materials which meet these requirements very effectively are 50% of solid density sintered iron and sintered tungsten. The sintered iron has a shock velocity of about 27 mm/μsec and the sintered tungsten a shock pulse velocity of about 2.3 mm/μsec. Since both of these materials have only 50% of their solid density, their compressibility is 50% plus, thereby giving a very high particle velocity which makes them very effective detonation initiators.

Aluminum will transmit a shock pulse with a minimum of attenuation, losing only 15% of its energy per inch of travel. Iron, on the other hand, exhibits two attenuation rates, one of which is extremely rapid until the pressure has dropped to 131 kb. This extremely large attenuation is due to a phase transition which occurs at pressures above 131 kb; as soon as the pressure has dropped to that pressure, however, the shock pulse is propagated with a loss of only 25% per inch of travel in the iron. This, then, provides a method of very rapidly dropping the pressure to 131 kb, by selecting the thickness of the iron beyond that point, a shock pulse of known intensity can be developed. We feel that this, in conjunction with low-order detonation, provides one of the most effective means of shaping detonation fronts.

The subject of low-order detonation is one which has been sadly neglected but which has great possibilities for wave shaping. Most people, even with long experience with military explosives, would probably feel that low-order detonation is an unpredictable phenomena, to be eliminated wherever possible. It is, on the contrary, a very reproducible phenomenon. In fact, there is a commercial process in operation today in which RDX is detonated at low order and used as a propellant.

We believe that under carefully controlled conditions most explosives will exhibit low order detonation and that each of them, when subjected to a controlled shock pulse, will follow one of four different behaviors, separated by very sharply defined boundaries:

a. There is a shock pulse intensity below which no detonation will occur.

b. There is a second shock pulse range within which low order will be initiated but will quench.

c. There is a third shock pulse range within which the low order which is initiated will change over to high order.

d. There is another critical shock pressure above which high order will always be initiated.

Whether low order will quench or go over into high order will, of course, be determined to a considerable extent by the geometry involved. Since the low-order detonation rate is in the order of 2 mm/μsec or less, and under controlled conditions and geometry is highly reproducible, we believe low order will be extensively used in detonation front shaping in the future.

Instead of the usual small difference in detonation rate, this provides a fourfold change, requires only a single explosive, and makes it possible to maintain a maximum of energy in a minimum of space.

Because of the special property of iron to rapidly attenuate the shock pulse, it is possible to obtain a high degree of wave shaping by placing a single sheet of steel of only slightly varying thickness between the initiating charge and the main charge. Such a steel barrier low-order lens in which a converging detonation front can be developed is shown in Figure 10.

The development of a circular or peripheral detonation is one of the easier types of initiation to obtain, merely by allowing an explosive to detonate over an inert barrier of some kind. Peripheral initiation provides one of the easiest ways of improving the performance of many charges.

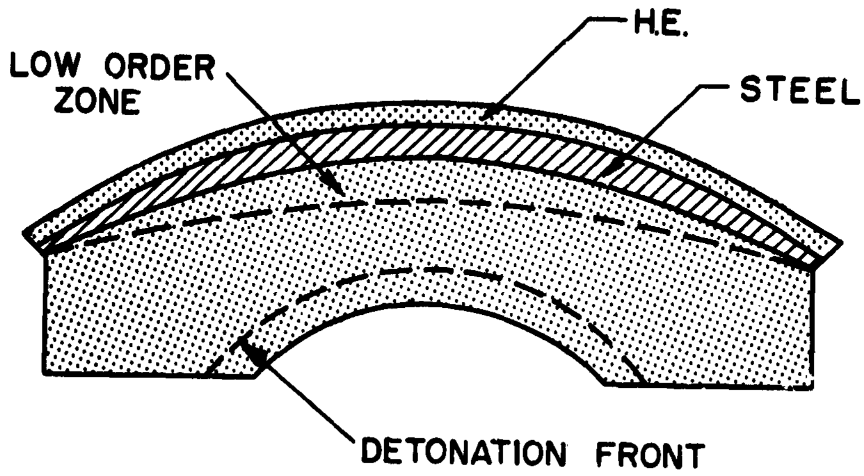


Fig 10 Steel Barrier Low-Order Lens

A 12-inch-diameter flat charge 3/4 inch thick placed on a 3-inch-thick plate of mild steel and detonated from the center will throw a spall off the back surface of the plate which is slightly larger in diameter than the explosive charge, reasonably uniform in thickness, and thinner than the explosive. On the other hand, if the same charge is peripherally initiated, the spall will be entirely different. Its diameter will be somewhat reduced, its thickness at the edge will be about the same or possibly less, but its thickness at the center will be about 2 inches.

Detonation Shaping vs Impulse

The detonation rate, as such, affects only the detonation pressure, whereas the impulse takes into account the length of time over which the pressure is applied and is frequently the dominant factor. The impulse resulting from the implosion of a spherical charge is, of course, completely symmetrical just as is the detonation pressure.

The effect of the relief pulse alone in a cylindrical charge (Fig 2) detonated by means of a plane wave from one end would be to develop a maximum impulse at the center which would drop off linearly to zero at the periphery of the charge. There is superimposed on this, however, an effect which tends to smooth out any abrupt change, and that is the confining effect of any charge case, or the surrounding atmosphere, plus the confining effect due to the momentum of the products of detonation. We

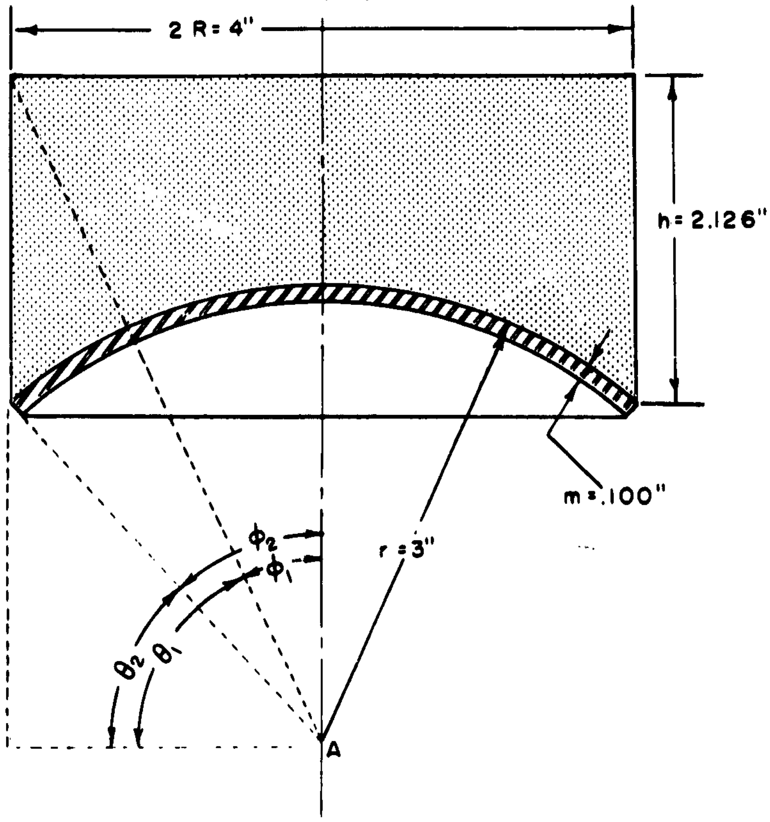


Fig 11 Existing Cylindrical Charge

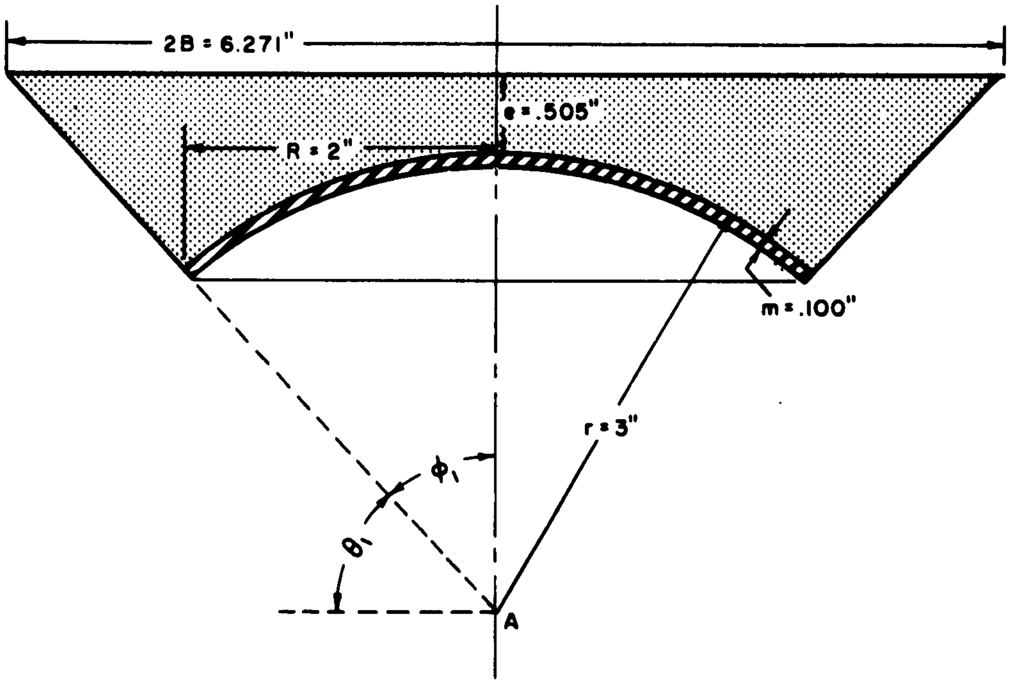


Fig 12 Modified Charge

believe, however, that because of the overriding effect of the variation of the magnitude of the impulse at various points on the detonation front, it is perhaps as difficult to determine what shape detonation front is desired as it is to develop it. We believe, therefore, that for most applications it is impractical to expend any appreciably effort in trying to develop a special detonation front without at the same time very seriously considering the impulse.

By way of illustration, an existing cylindrical charge (Fig 11) containing a spherical section steel liner was centrally initiated from the opposite face. When this charge was fired, the central portion of the liner advanced ahead of the periphery of the plate forming nearly a spherical shell which then broke open at the center and turned inside out and disintegrated. It was desired to modify the charge so that the plate would advance substantially as a solid flat plate. The first move was to modify the shape of the charge (Fig 12) so as to increase the quantity of explosive back of the periphery of the plate, and then to peripherally initiate the charge so as to let the detonation front strike the periphery of the plate first. The resulting charge projected the plate into a comparatively small diameter jet with the center of the plate forming the forward end of the jet. The quantity of explosive was reduced behind the center of the plate and increased around the periphery of the plate, and the detonation front was modified so as to strike the periphery of the liner several microseconds before it did the center of the liner. Even so, this change in design had accentuated the impulse at the center of the plate over that at the periphery of the plate to such an extent that the velocity of the plate at the center had been more than doubled, whereas the velocity at the edge of the liner had remained essentially unchanged. From flash X-ray and flash photographs it has been possible to follow the progress of the plate (Figs 13 and 14, pp 43, 44) from the time that it started to move throughout the first few feet of travel.

Let us consider a lined charge of uniform thickness (Fig 15) lined with a metal liner of uniform thickness and detonated with a detonation front which conforms to the back surface of the charge. When such a charge is fired it is found that the metal plate experiences a very much higher acceleration along the axis than it does at the periphery. What can be done to the shape of the detonation front to correct this and give the

plate a nearly uniform velocity at all points? Any change in the shape of the detonation front to cause the detonation front to strike the periphery of the plate earlier would, of cource, tend to start the periphery of the liner to move a little earlier with respect to the center, but such a change would at the same time increase the convergence in the charge at the center and, hence, increase its velocity along the axis. The only effective procedure will be one which reduces the convergence at the center with respect to the periphery.

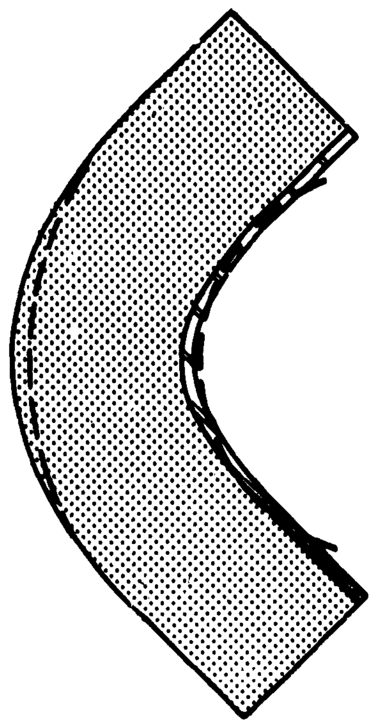


Fig 15 Lined Charge of Uniform Thickness

For the first approximation, an arc should be drawn through the liner which matches the liner as closely as possible. Then from the center of curvature of this arc another arc should be drawn through the rear of the charge. A spherical detonation front of this shape will give a very marked improvement, but it will be found that the axis is still a little high.

The best procedure from this point would be to measure the actual liner velocity at various points by means of a smear camera, flash X-ray,

or pin machine and then, disregarding the arrival time of the detonation front at the surface of the plate, modify the curvature of the detonation front by increasing the radius of curvature at points where the velocity is high and decreasing it where the velocity is low. In other words, the detonation front is shifted in the direction that would tend to make it more nearly conform to the shape of the liner after it has advanced a short distance.

We therefore feel that it is feasible to develop detonation fronts conforming to almost any simple geometric form, such as:

1. Spherical convex
2. Spherical concave (implosion)
3. Conical concave
4. Conical convex
5. Cylindrical concave
6. Cylindrical convex
7. Toroidal, or sections of toroidal, concave
8. Toroidal, or sections of toroidal, convex
9. Polygonal converging in a flat sheet
10. Polygonal converging in a flat sheet with concave or convex sides
11. Parabolic concave and convex
12. Hyperbolic concave and convex
13. Elliptical concave and convex

We would again like to caution, however, th the impulse and not the shape of the detonation front may be the dominating factor.

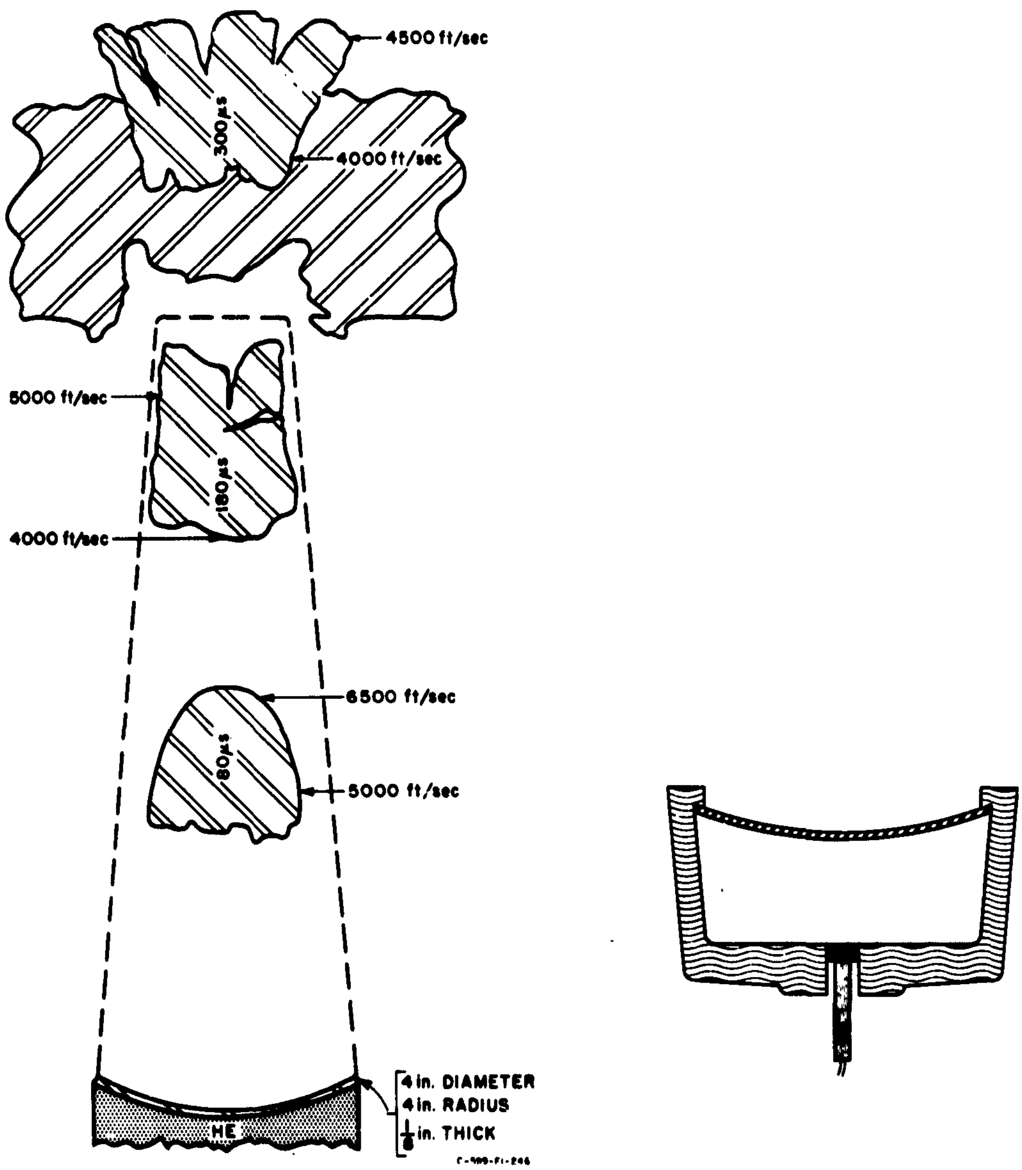
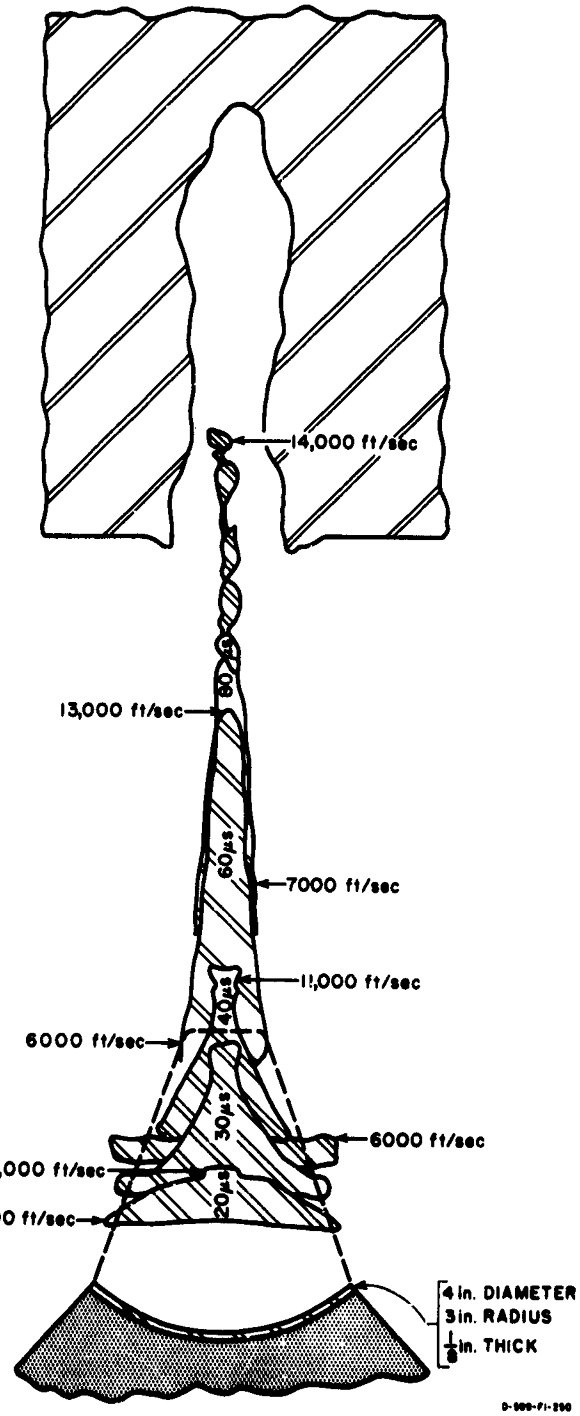


Fig 13 Diagram Representing Firing of Unmodified Cylindrical Charge



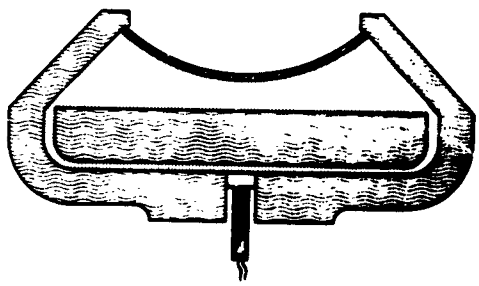


Fig 14 Diagram Representing Firing of Modified Charge

PRINCIPLES OF WAVE SHAPING

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ABSTRACT

A general review of the history of detonation wave shaping is given. Principles which have been considered are discussed and commented upon. The use of geometric optics in lens design is indicated. There are some specific variations of the NOL type lens which are discussed.

INTRODUCTION

For the purpose of this discussion, wave shaping will be confined to shaping of detonation waves. The normal situation for detonations is that they are initiated at a point and propagate spherically from this point. This propagation is at essentially constant velocity. As a consequence, the spherical wave increases in radius in direct proportion to the time. Wave shaping can then be considered as any perturbation of the wave propagation, such that the wave front does not increase in radius in proportion to the time. In this sense the initiation of an explosive charge simultaneously at two points would not cause wave shaping so long as the waves from each point do not intersect. If the two points of initiation are close relative to the distances traveled, however, the waves will meet and a region in which the two waves propagate nearly parallel can be considered the region in which the wave has acquired some degree of shaping.

One of the simplest ideas of wave shaping is therefore suggested, which is to increase the number of points of initiation many fold so that the front after intersections occur propagates in some more or less distinct pattern. An extension of this idea is also suggested, namely, the insertion of barriers such as are used in the peripheral initiation of shaped charges. A wave pouring over a barrier propagates as if the barrier edge has become a new source of initiation and the wave propagating from this barrier is considerably different than that propagating from a point. The result is similar to the propagation of a water surface wave around an obstruction.

It is well known that detonations and shock waves propagate in different media at different velocities. This suggests that waves can be continuously shaped by the introduction of barriers which transmit the wave, just as glass reshapes and redirects an optical wave by slowing it down in transit through the glass. If the glass-air boundary is given a spherical shape, the wave can be focused upon passage across the boundary. Similarly, if one chooses explosives of two different propagating velocities, the detonation wave can be focused upon passage across a curved boundary. The fast-slow combination becomes one of the basic ideas of explosive wave shaping, the explosive lens. Most of the discussion to follow will bear on the problems incident to the development of explosive lenses having qualities which make them efficient and practical for application to research devices and military weapons.

HISTORICAL

To the writer's knowledge, it was not until after World War II that the state of the science and art related to the detonation of explosives had reached the point of sophistication where people began to think about shaping or controlling the detonation wave front. The first suggestion in this direction seems to be due to H. J. Poole in September 1942 (Ref 1). In a relatively short memorandum Poole outlined the method for using a combination of fast and slow explosive to modify a detonation wave front. This suggestion was tested at Buxton by D. W. Woodhead and R. Wilson (Ref 2) and shown to be feasible. A plane wave lens based on this suggestion was made by J. H. Cook (Ref 3) and reported in the open literature. Cook used a cast explosive as the fast component and a low-density granular explosive as the slow component.

To the writer's knowledge, the first efforts to study wave shaping in this country date back to about early 1944 when Elizabeth Boggs and George Messerly undertook to develop a number of ideas with regard to shaping of detonation waves at the Explosives Research Laboratory, Bruceton, Pennsylvania. Among other things, they repeated the work of Woodhead and Wilson, using Composition B in cast form as the fast explosive and low density TNT as the slow component. They recognized at the outset that a granular explosive was a relatively impractical component to use for this purpose. As a consequence, they undertook an extensive program to search for castable explosives to be used as a low velocity component. Their first efforts included a study of baranal and sodatol. They later began to

experiment with baratol. In their early efforts difficulty was experienced in obtaining detonation velocities much below 5500 m/s without failure in propagation.

Paralleling the work of Boggs and Messerly, E. H. Eyster and his group at Burceton undertook to formulate compositions which could be cast and which had lower propagation velocity. It was L. Weltman who first suggested that sufficient barium nitrate could be gotten into a baratol by using a "gap-graded" material, that is, a mixture of coarse and fines to maximize the bulk density of the barium salt. This led to the formulation of 73/27 barium nitrate/TNT as a suitable low velocity explosive. Its detonation velocity in large diameter sticks is about 4900 m/s. When used with Composition B, a fast-slow ratio of about 1.6 results.

While these studies were going on, the Messerly group carried out a fairly broad brogram to study shock propagation through inert materials with the objective of finding some inert material which could be suitably used as the delaying medium for wave shaping purposes. Of these that were studied, lead, camium, and lead oxide looked fairly promising. They had propagation velocities in the vicinity of 4000 m/s. I have recently learned that this group also considered the use of air shock and the surface motion of a metal plate as a delay element. The former was ruled out as being impractical. The latter was tested but incorrect parameters were chosen in designing a lens with it and it was given up as being too difficult to develop. This group also studied multiple point initiation using PRIMACORD leads and thin layers of plastic explosive as leads to propagate the detonation into a large number of points from which a wave which is nearly flat could be generated. About this time it was found that multiple point initiation, though leading to reasonably flat wave front caused undesirable after effects due to the interaction of the detonation waves at points of meeting.

One of the needs for generating plane detonation waves was the study of the equation of state of solids, particularly metals, under shock. For this study the mathematics of the problem is considerably simplified in plane geometry. The studies of this kind were first conducted at Los Alamos by R. W. Goranson (Ref 4) and his co-workers. The Naval Ordnance Laboratory became interested in these studies in early 1947. We developed our own plane wave boosters at this time. Later, through the cooperation of Los Alamos, we began to use the plane wave lenses produced at the

Naval Ordnance Test Station. In late 1950 we were informed that production of these lenses would no longer be available to us. Fortunately for us, about that time the idea of using an accelerated metal plate traveling through an air gap to delay a detonation occurred to me. Having the need for a local source of high quality plane wave lenses, we pursued this idea and in less than a year had developed it to the point where it could be used in our research program (Ref 9).

One cannot think about wave shaping very long without considering the possibilities of developing wave shapes other than plane. Back in 1945, R. H. F. Stresau and W. W. Rymer (Ref 5) looked into the possibility of producing spherically convergent waves. Their work stems from a suggestion by Dr. George Gamow, made in late 1944. They showed that theoretically a spherically convergent wave could be generated from a fast-slow explosive combination by designing the interface as a logarithmic spiral. They actually performed an experiment in sandwich form with Composition C and granular TNT in which they carried the spiral 180°clockwise and counter-clockwise from a single initiating point and showed that the wave did, in fact, converge to about a point in the central region. The double spiral gives the appearance of a valentine, and so this charge became known as the Valentine charge. The same idea was suggested earlier at Bruceton by E. Boggs in 1944, but unfortunately never found its way into a formal report.

METHODS OF WAVE SHAPING

By way of review it might be of use to outline methods that come to mind to create detonation waves having a predetermined shape. The first and most elementary would be multiple point initiation. This might be accomplished in the following ways:

a. The Use of Branched PRIMACORD. A large bundle of PRIMACORD leads can be simultaneously initiated from a single detonator and booster. These leads can be oriented to transmit an initiation pulse to the surface of an explosive charge. Suitable choice of length and spacing of the lead ends can cause the average wave front in the explosive to have a desired shape. Although this idea will work in principle it does have some inherent drawbacks. First, an assembly becomes rather complicated and difficult to put together. The propagation velocities in PRIMACORDS vary sufficiently for

deviations in the arrival of the wave at the new boundary to get to be as large as ½ μsec. The number of points that can be used must be limited by practical considerations, so that over large areas the wave front can be considerably rippled and troublesome detonation wave interaction effects can develop.

b. Multiple Lead Systems. The idea of the PRIMACORD leads can be developed into a more compact package by using leads which are worked into an inert matrix, much as printed wiring makes electrical circuitry more compact than normal wiring. This approach gives considerably greater opportunity for branching to a large number of points in a small package. It, therefore, can improve on branched PRIMACORD by a large factor. Wave interaction effects may still remain but they would cartainly be less troublesome because of the opportunity of having a larger number of initiation points.

c. Simultaneous Detonators. Relatively small detonators have been developed. These can be made reproducible to about 1/20 μsec (Ref 6). A large number of detonators fired simultaneously can produce the same effect as multiple PRIMACORDS with less packaging difficulties. One of the drawbacks of multiple detonators is the problem of maintaining detonating safety.

The methods based on continuous delay of the initiation along an explosive boundary may be next considered. They include:

a. Fast-Slow Explosive Lenses. The combination of fast and slow explosives is a very practical way to create detonation waves of desired shape especially when there is no limitation of space. The amount of material needed to produce the wave is closely linked up with the index of refraction, that is, the ratio of fast to slow detonation velocity. The baratol-Composition B combination has an index of refraction of about 1.6. All efforts to produce reliable detonation at velocities below 4000 m/s have been rather unsuccessful (Ref 7). The upper value for the fast component velocity seems to be practically limited to about 9000 m/s, so that the index of refraction cannot be expected to exceed 2.25. In addition, this type of lens requires a high degree of quality control for two explosive components, so that precise lenses become rather costly. In spite of the problems encountered many wave-shaping devices have been built along these lines. We have used pentolite-baratol lenses for a number of years in our work. Composition B-baratol lenses have been made in diameters up to 8 inches and used in several explosive research laboratories.

b. Shock Delay Lenses. Replacing the low-detonation-velocity component by an inert medium which transmits a shock of adequate strength at low velocity has some promise of increasing the index refraction. However, at this time it does not appear that the shocks will reliably initiate the explosive when propagating at less than 3500 m/s. As a consequence, shock delay lenses are limited to an index refraction of about 2½ to 3. The use of air shocks has several drawbacks. In the first place, they probably would have to propagate at about 5000 m/s to give reliable initiation. The propagation velocity of air shocks generated by explosives and subsequent initiation is likely to be sensitive to the ambient density of the air. Consequently, a lens designed for atmospheric pressure at one temperature is likely to perform differently when the pressure and temperature change. Shock delay lenses were studied at NOL and given up because of the fact that they seemed to offer no great advantage over the fast-slow explosive combination. The work has been carried on with some success at Utah University (Ref 8) and at the Poulter Laboratory, Stanford Research Institute. The Utah lenses are certainly simple and practical for laboratory use. Because of their large effective focal length they may, in fact, be more ideally suited for precision plane wave applications where wave perfection may be more important than economy of explosive weight.

c. Transfer Lenses. This type of lens can best be represented by what we at NOL have termed the NOL plane wave booster (Ref 9). It has also been termed an air lens because the metal transfer plate has a free run through an air gap. The people at Bruceton called this a projectile lens. It has been found at NOL that it is possible to create a lens in this way by accelerating a metal plate or sheet to velocities of about 1000 m/s with an explosive having a velocity of about 8000. This means that a desired wave shape can be developed over a relatively large area in a short distance of travel normal to the surface to be initiated. Although the principle does not involve a wave, it is still convenient to think of the projection velocity of the metal as the slow component velocity and to think of the lens having an index of refraction. In this particular case, the index can be as high as 10 or 12, which is indicative of its ability to shape the waves in a small volume. Several advantages can be seen for this type of wave shaping. For one, there are few limits on the explosives that can be used. Most acceptable military explosives will work. The reliable functioning of this device depends mostly on the uniformity of the donor explosive (the explosive that accelerates the transfer plate), uniformity of the acceptor boundary, and the uniformity of manufacture of the transfer plate itself.

The transfer plate is manufactured by standard machine shop operations and can be made to considerably better tolerances than machined explosives. Because of the high index of refraction, many designs are possible with this device which are impossible when the index of refraction is two or less.

An additional method for limited wave shaping is represented by the following:

Line Initiation. The peripheral initiator is representative of this principle. Here a wave obstructed by a barrier initiates over a circular line to produce a toroidal wave in the charge. The idea has been extended at the Poulter Laboratory to combine a preliminary shock through the barrier of insufficient strength to initiate the explosion with a peripheral detonation. The result is that an increased pressure can be expected near the axis. This will be advantageous in some applications to weapon design. The shaped charge may be cited as one case. The combined effects of shock and detonation should be studied farther to determine how far one may go in this direction to get more energy and impulse into the localized central region.

GEOMETRIC OPTICS

The shaping of detonation waves by slow explosives, shocked media, and transfer plates can be readily analyzed by the use of geometric optics. The simplest analygy would be that of an optic lens. A detonation in a fast explosive could pass after some distance of travel across a plane-convex or double-convex lens made of slow explosive and then back to the high-velocity explosive to give a wave which is plane (that is having parallel rays), convergent, or divergent (Fig 1). All lens laws would apply as long as the proper index of refraction was used. Because plane waves are representative of all focusing problems, discussion will be limited to this case. In using a lens for shaping detonation waves it is desirable that a minimum amount of explosive be used in the unshaped region. This is the same as saying that lenses of very small f number are most desired (f number as in optics can be defined as the focal length divided by the diameter). Detonation waves differ from some electromagnetic waves in one property. The "rays," unlike light rays, can enter the slow medium at glancing incidence and still be transmitted in the slow medium. As a consequence, the amount of explosive in the unshaped region can be minimized by reducing the boundary from a spherical surface (actually an approximation to a hyperbola) to a conical surface. The center of initiation then must be the apex of the cone (Fig 2).

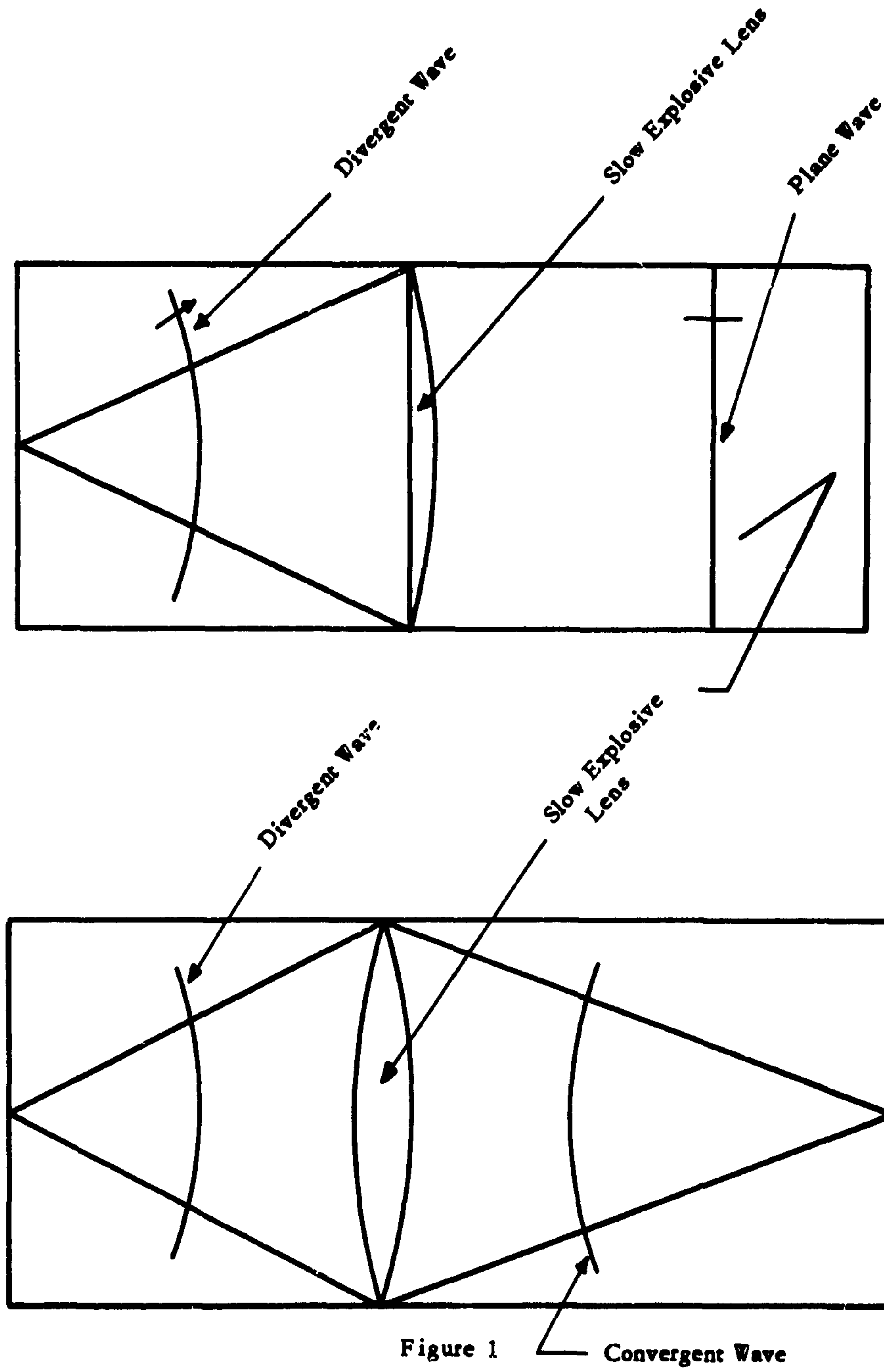
Divergent Wave
Slow Explosive Lens
Plane Wave
Divergent Wave
Slow Explosive Lens
Convergent Wave

Figure 1

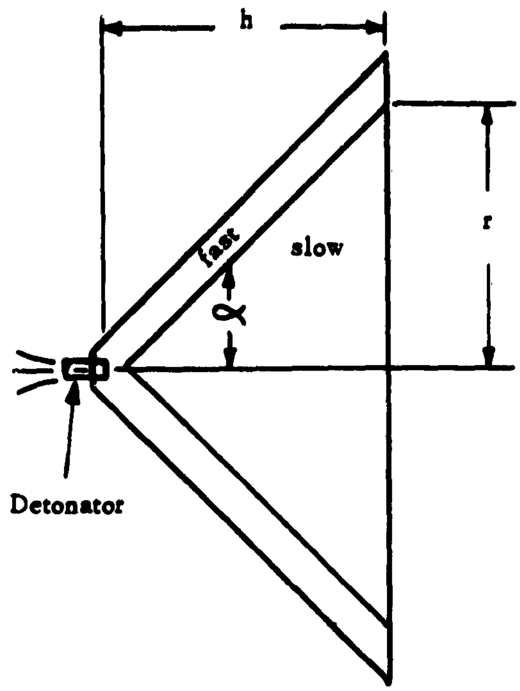

Figure 2

If it is desired that the center of initiation be removed a small distance from the boundary the interface becomes a hyperbola. A possible variation is to place the plane surface of the slow explosive at the detonotor side and shape a second boundary where the detonation passes back from the slow explosive to the fast explosive as shown in Figure 3.

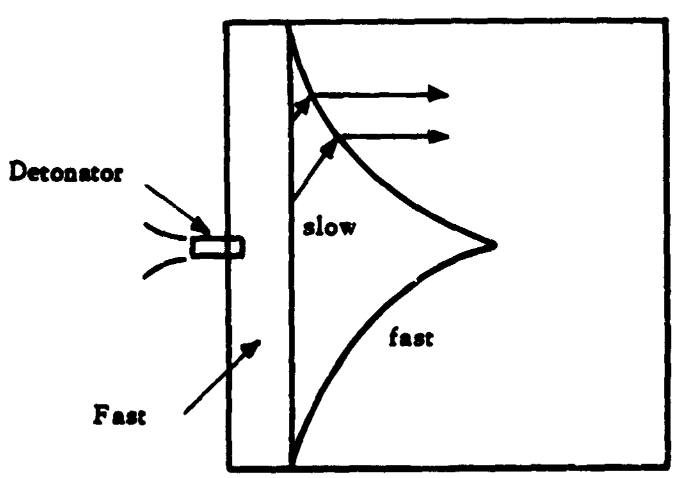

Figure 3

The shape indicated by Figure 2 has a lesser height of slow explosive than that as shown by Figure 3 and is therefore more efficient. In the cone model the height of slow explosive is given by:

$$h = r/\tan \alpha$$

where

$$\cos \alpha = V_s/V_f = 1/n$$

V_s is the propagation velocity in the slow medium, while V_f is the propagation velocity in the fast medium and the index of refraction, n, is the ratio of the fast to slow velocity. It can be seen that the larger the value of n the smaller will be the ratio, h/r. When n becomes very large, the choice between the design of Figure 2 and that of Figure 3 becomes less important in regard to the effect on h/r.

In the transfer or air lens the equivalent of the single-line boundary can be approximated as a flat metal plate of constant thickness. If the metal plate is flat, like the first boundary of Figure 3, and the detonator is removed a small distance from the boundary, the second surface becomes approximately parabolic. If the second surface is flat as in Figure 2, the transfer plate of constant thickness approximates a hyperbola. In the limit for very large n the height h approaches r/n. The ratio h/r for the baratol-Composition B lens is about 0.8 whereas the ratio for a satisfactory NOL type booster is about 0.12, a sizeable reduction.

PROBLEMS OF LENS DESIGN

One of the major problems of the two explosive type lenses is the development of a slow explosive which propagates reliably and detonates the explosive to which the wave is to be transferred. It is probable that the choice of TNT as the base explosive could be improved on. It would probably be more desirable to degrade a more sensitive explosive to get the low detonation velocity. Efforts have been made in this direction at NOL. For example, tetryl has been degraded with salt and other materials. The result, however, has been to show that 4000 m/s is about the lower limit of reliability (Ref 7). No effort was made to see how well the detonation would transfer from this slow medium back to materials like Composition B. It is fairly certain, however, that the transmitted shock pressure is marginal though adequate for reliable initiation.

In a shock delay lens the energy for detonating the acceptor explosive must be delivered by the layer of donor explosive behind the slow component. To transfer sufficient shock pressure for reliable initiation, the shock velocity in the inert parts must come quite close to the detonation velocity in a slow explosive so that the advantages of shock delay are not too great if the h/r ratio is to be minimized. Studies on initiation through barriers or gaps give us information about the maximum gap possible (Ref 10).

The transfer type of lens appeared extremely promising in view of the fact that the "wave velocity" with a transfer plate would be essentially the equivalent of the particle velocity in the explosive or a shocked medium. It appears at this writing that the transmission of an initiating pulse by a delaying medium is at the slowest possible velocity when the delaying mechanism is the free flight velocity of a material of high shock impedance. Shock propagating media must by their very nature transmit the pulse of velocities much higher than the particle velocity, usually in excess of four times the particle velocity for dense media such as solids or liquids.

It is well known that the particle velocity in a good military explosive is about 2000 m/s. It was, therefore, first believed that a transfer plate would have to move at about this velocity to give reliable initiation. 2000 m/s, however, already indicates an index of refraction of 4 as compared to about 2½ as the best obtainable by other means. We have since learned that considerably smaller impact velocities can give reliable detonation so that an index of refraction of 12 is not impossible. In striving for this high index we approach the initiation problem which exists for slow explosive and shock types at indices like three. One of the problems in designing for minimum transfer velocity is to understand the initiation process for impact initiation so that we can establish how far we may go. High-index lenses lead to another problem. With transfer plate velocities as low as $\frac{1}{10}$ of the detonation velocity it becomes necessary to manufacture the air gap to much higher tolerance because the time interval for unit distance of travel is so much greater. In spite of this problem, time reproducibility as good as or better than shock types is possible.

Failure to initiate under part of a lens can become a serious problem. An interaction of detonation waves, particularly at a point as a result of

failure in a circular region, can lead to abnormally high pressures in the region of interaction. A deliberate degrading of the transmitted shock below the point of initiation can be turned into an asset under some circumstances, as has been shown by Dr. Poulter and his collaborators at Stanford (Ref 11).

SOME ASPECTS OF TRANSFER LENS DESIGN

A transfer lens developed at NOL started out with a curved metal disc of constant thickness. This required that two surfaces of the metal plate be formed to a precise curvature of rather arbitrary shape. Shortly after the inception of the idea, we switched to a design in which a flat metal plate was accelerated into a cavity behind which the explosive surface was shaped. From a fabrication point of view, this was simpler because the plate was flat and could be made without difficulty. Only one free-form surface had to be developed and this could be made in the mold used to cast the acceptor explosive. I had envisioned a wave shaping device which should work but has never been tried. It would consist of a flat metal plate accelerated into a free-form cavity formed into an inert plastic like lucite. The opposite boundary of the lucite would again be a plane (Fig 4). A device such as this has the external appearance of a flat sandwich. Wave shaping would be produced by this device by merely placing this sandwich between two flat slabs of explosive. All machined surfaces would be in inert material so that explosive fabrication would be at a minimum. Mr. Liddiard, of the Naval Ordnance Laboratory, has developed an alternate type of transfer plate lens in which the transfer plate varies in thickness as a function of radius. This could be called a variable index lens. Liddiard's lens could easily be made into a flat sandwich by arranging the design as shown in Figure 5. Again all machined parts are inert.

The principle of the air lens is by no means confined to the geometries described in this paper. The lens could, for example, have cylindrical symmetry to develop a cylindrically expanding wave from a point source. We have developed a model of this lens which could be applied to the TALOS warhead in which the explosive is located in an annulus between two cylindrical surfaces. Our concept of lensing this warhead to get a detonation wave traveling uniformly parallel to the axis was to use eight sectors simultaneously initiated by simultaneous detonators, primacords, or other type leads. This combination of lens and multiple point initiation might be the answer to an improvement of the performance of the continuous-rod warhead. An air lens can probably be effectively designed into a shaped

charge warhead. Here some convergence would be wanted near the apex of the cone to increase the tip velocity of the jet. Continuous wave shaping in this application might prove more effective than peripheral initiation. In order to converge over a larger solid angle it might be desirable to shape the wave with a segment of a sphere which is accelerated inward by a uniform layer of donor explosive.

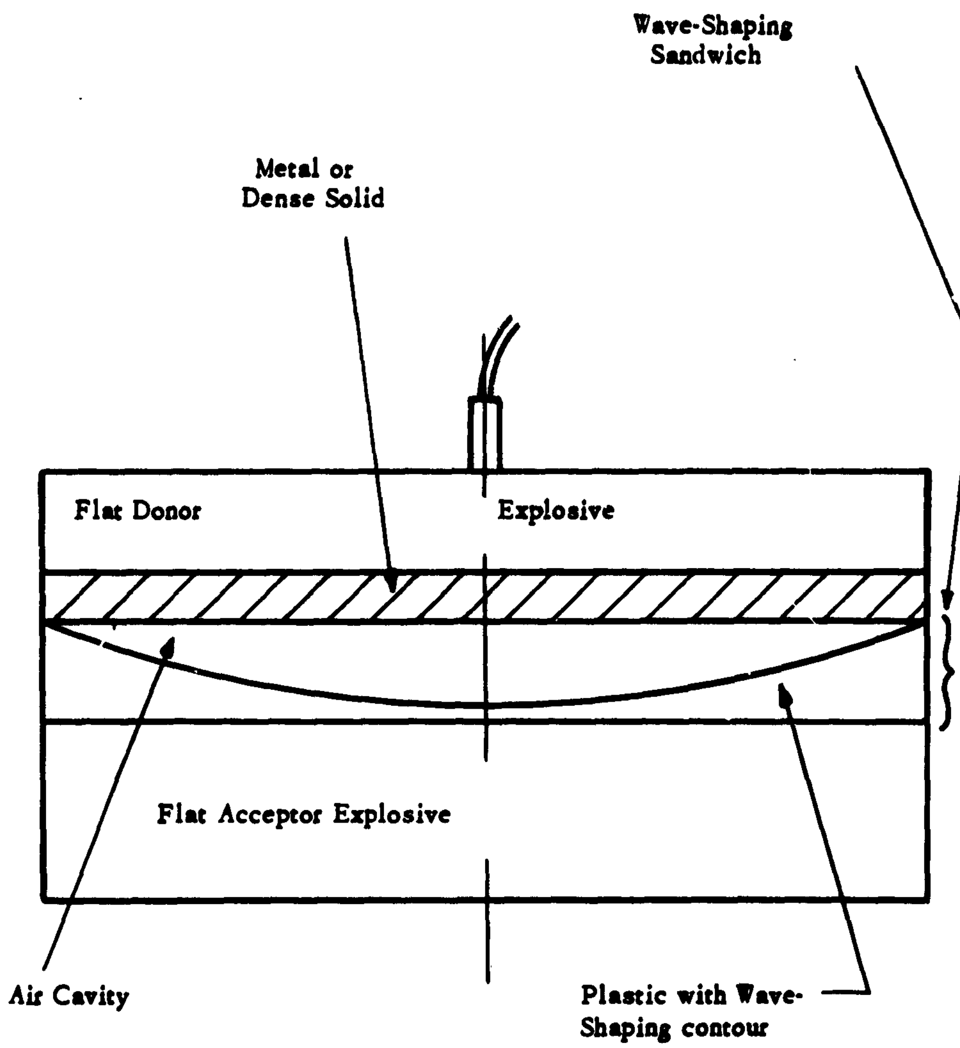

Fig 4 Inert Sandwich Wave-Shaping Device

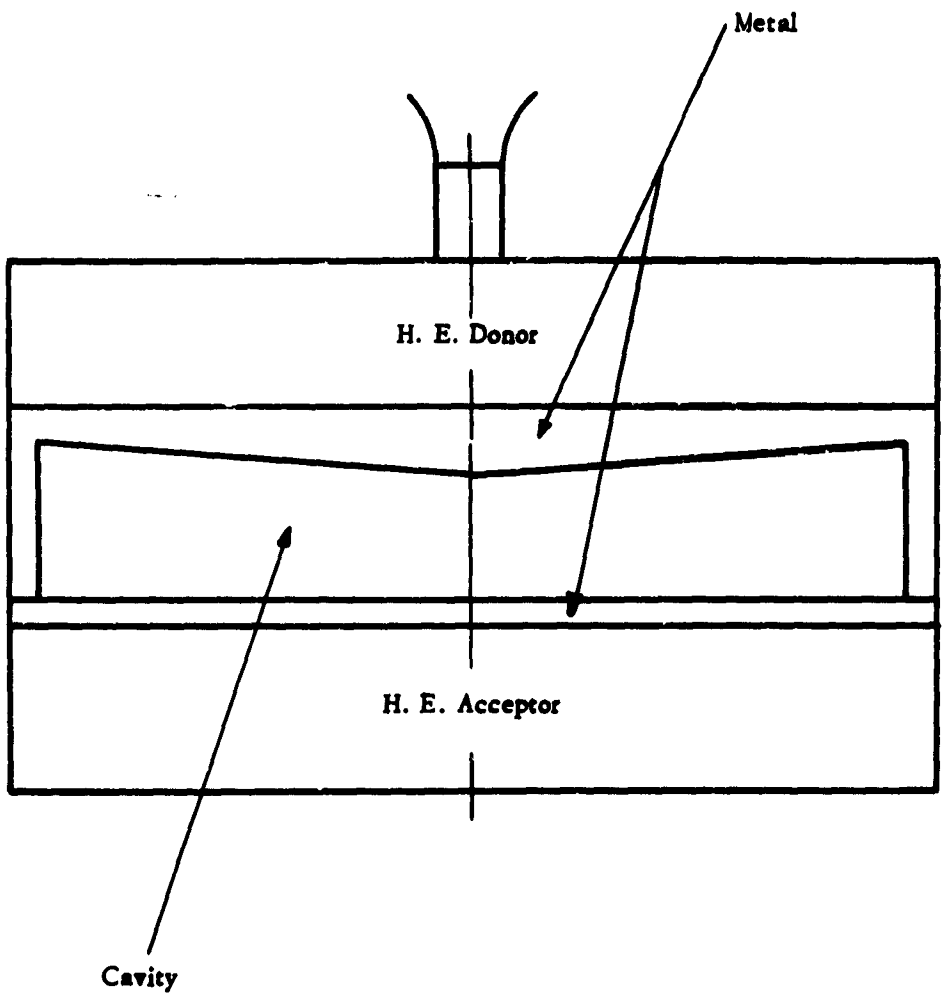

Fig 5 Modified Variable Index Lens to Shape a Wave in a Flat Sandwich

APPENDIX I

SHOCK RELATIONS FOR TRANSFER PLATE IMPACT

Consider a transfer plate moving at velocity u_1 impacting on an explosive at velocity U_2. Behind the shock the particle velocity will be u_2, which is also the boundary velocity. A shock moving at U_1 relative to the moving transfer plate will travel to the left (Fig 6). Let ρ_{10} and ρ_{20} be the respective initial densities of transfer plate and explosive.

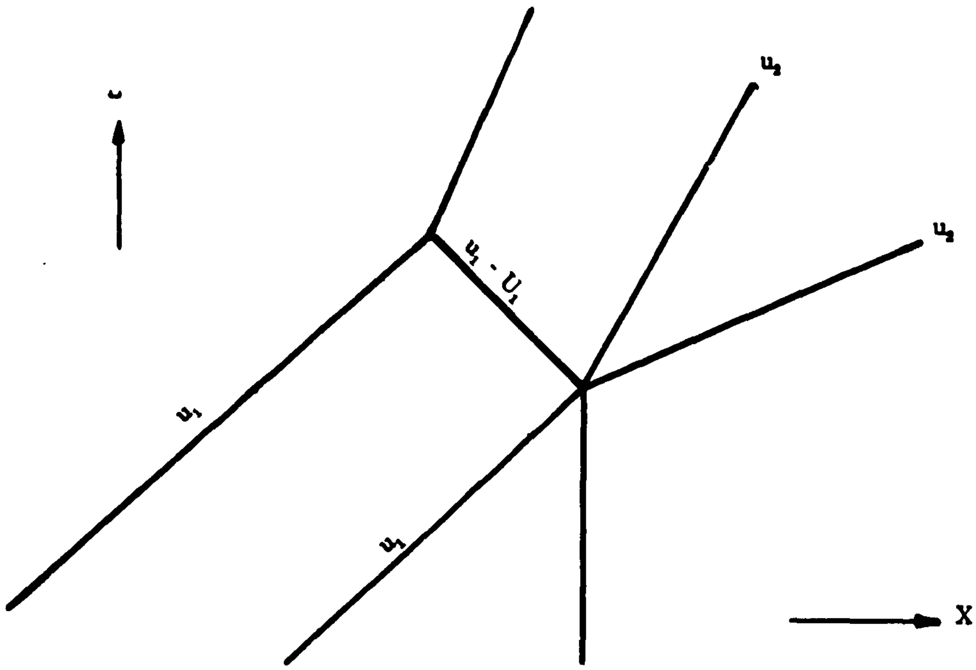

Fig 6

The pressure along the boundary must satisfy the relations:

$$p_2 = U_2\,\rho_{20}\,u_2 \qquad (I - 1)$$

$$p_2 = U_{10}\,\rho_{10}\,(u_1 - u_2) \qquad (I - 2)$$

since u_2 must be the same in both media.

Solving for u_1 as a function of u_2, we get:

$$u_1 = u_2\left(\frac{U_2\rho_{20}}{U_1\rho_{10}} + 1\right) \qquad (I - 3)$$

$$= u_2\,(Z_2/Z_1 + 1) \qquad \text{(I - 4)}$$

where Z, the shock impedance, is defined as $U\rho_0$ with proper subscript.

This shows that as Z_1 becomes very large relative to Z_2, the transmitted particle velocity approaches the transfer plate velocity. Since u_2 will have to exceed some minimum value determined by the initiation delay which should be a function of u_2^7, it is seen that u_1 will be smallest when Z_1 is as large as possible. For steel Z_1 will be about 40 (U in mm per μsec, ρ in g per cc) Z_2 will be somewhat less than $D\rho_{20}$ (D, the detonation velocity). A good estimate will be about 10. This makes u_1 about 1.25 u_2. For aluminum, Z_1 will be about 20 and u_1 will be about 1.5 u_2. Very dense materials like tungsten would lower u_1/u_2 to about 1.1. Very light materials like lucite would raise u_1/u_2 to about 2 or perhaps a little more.

APPENDIX II

SHOCK RELATIONS FOR SHOCKS FROM INERT OR EXPLOSIVE TO EXPLOSIVE

In this case (Fig 7), a shock at velocity U_1 impacts on the boundary and transmits a shock U_2. A shock U_r is generally reflected (it might be a weak rarefaction wave).

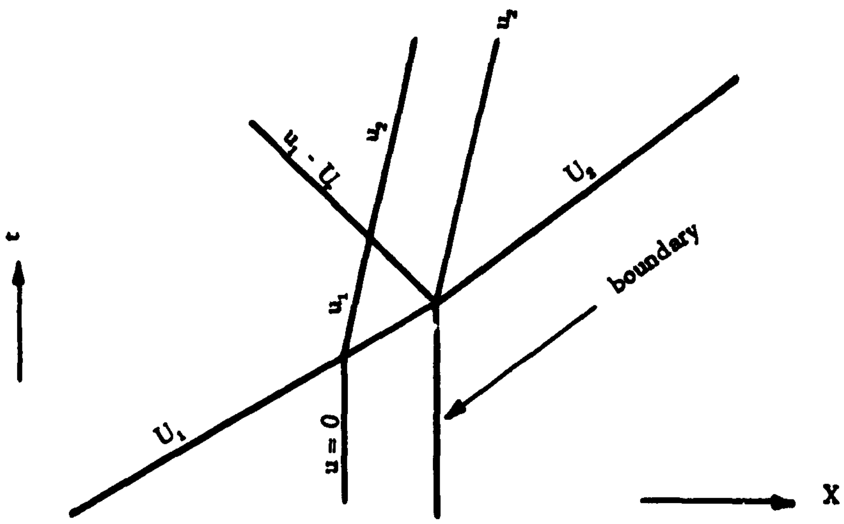

Figure 7

For the shock reflection case:

$$p_2 = U_2\, \rho_{20}\, u_2 \qquad \text{(II - 1)}$$

$$p_2 - p_1 = U_r\, \rho_{11}\, (u_1 - u_2) \qquad \text{(II - 2)}$$

$$p_1 = U_1\, \rho_{10}\, \bar{u}_1 \qquad \text{(II - 3)}$$

Eliminating pressures and writing $Z = U\rho$ with appropriate subscripts:

$$u_1 = u_2\, \frac{Z_2 + Z_2}{A_1 + Z_2} \qquad \text{(II - 4)}$$

A usually acceptable approximation is to write $A_2 = Z_1$. The approximate

relation for u_1 vs u_2 is then:

$$u_1 = u_2 \left(Z_2/Z_1 + 1 \right) / 2 \qquad \text{(II - 5)}$$

When Z_2/Z_1 becomes small, u_1 approaches $u_2/2$. For the numbers used in Appendix I, steel to H.E. would give $u_1 = 0.625\ u_2$. For aluminum, u_1 would be about $0.75\ u_2$. For u_1 to be small for a given required u_2, Z_1 must be comparable in magnitude to Z_2(or larger). This implies. $U_1\rho_{10} \gtrsim 10$. A moderately high density at a low shock velocity is implied. It would appear unlikely that U_1 will be anywhere near as low as u_2, as is the case for a transfer plate. The shock velocity in steel would exceed 5 mm per μsec and in aluminum would exceed 5.5 mm per μsec so that these materials would produce only low index lenses. Sintered metals, metal loaded plastics, lead, or cadmium might be better choices as the delaying medium.

APPENDIX III

The arguments advanced in Appendices I and II are predicted on the assumptions that the explosive before reaction acts as an inert compressible fluid and that the explosive has therefore a shock Hugoniot, as does water. It is argued that a shock pressure and temperature above a given thresholdvalue are needed to start a reaction which is capable of building up to a detonation in a reasonably short and reproducible time. Referring to Figure 8, a point, p_s, on the shock Hugoniot must be exceeded by impact before the reaction will be built up to a stable detonation in some arbitrarily short time, say ½ μ sec or less. We argue that the scatter in initiation delay across a surface and between shots will be of the order of

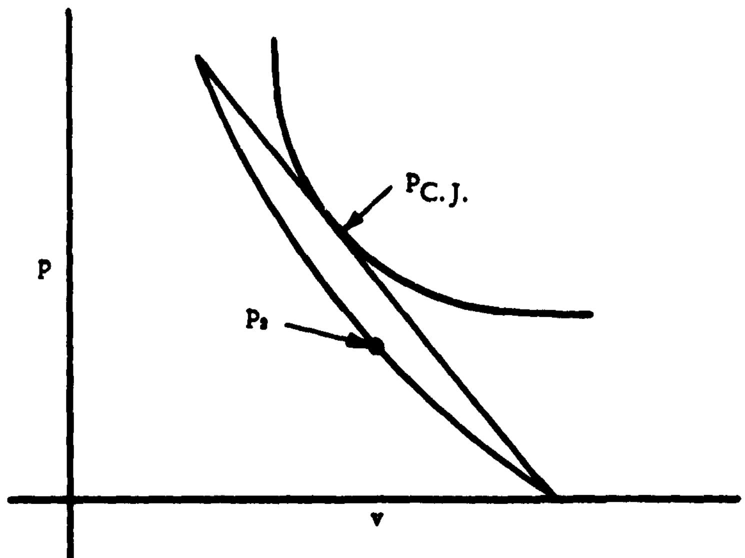

Figure 8

5 to 10% of the delay itself, so that lens design can proceed using geometric optics on the basis that the delay will be about the same throughout the surface of impact. Undoubtedly part of the correction made after an initial trial will be due to a deviation from the assumed equal delay. The scatter from shot to shot after corrections are made is certainly small or we would not have been so successful in getting reproducibility in our lenses already designed. The lower limit of impact velocity for both transfer and shock delay lenses is reached when the initiation delay becomes erratic. This limit will be a function of the explosive used as acceptor.

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THE EFFECT OF SHOCK STRENGTH ON THE INITIATION OF HIGH EXPLOSIVES

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ABSTRACT

Delay times in initiation of high explosives as a function of known shock strength were determined for 65/35 HMX/TNT, 75/25 Cyclotol, Composition B, Pentolite, and TNT.

INTRODUCTION

In many wave-shaping designs, thin layers of explosive are used to initiate an acceptor explosive through a metal barrier. To arrive at a desired wave shape, prior knowledge of delay time in initiation to high-order detonation is required. However, to the author's knowledge, no quantitative studies of the effect of known shock strength on the initiation of high explosives, other than the work of Sultanoff and Bailey[1] on initiation through air gaps, have been reported. This report describes an attempt made to study the delay times in initiation as a function of known shock strength through a metal barrier. Delay time in initiation will be tentatively defined as the difference between the measured transit time and the theoretical steady state time for the same distance of travel by the detonation wave. As additional knowledge is accumulated, it is anticipated that a new definition will have to be adopted. The theoretical time will be determined by assuming a detonation velocity independent of charge diameter. The delay time found could thus be considered at that time which is required to establish the steady chemical reaction zone in a steady state detonation. A measure of the shock strength will be given by the free surface velocity of the aluminum barrier. This quantity can be easily converted into pressure with any available data such as that

[1] D. M. Sultanoff and R. A. Bailey, *Induction Time to Sympathetic High Order Detonation in an Explosive Receptor Induced by Explosive Air Shock*, Ballistic Research Laboratories, Report No. 865, May 1953

given by Walsh and Christian[1]. Results will be presented for five cast explosives, Composition B (fine grain RDX), pentolite, 75/25 cyclotol, 65/35 octol (HMX/TNT), and TNT.

EXPERIMENTAL PROCEDURE

The explosive assembly shown in Figure 1 consisted of a 0.4" x 3" x 12" slab of explosive (65/35 HMX/TNT) sandwiched in 11/16" x 3" x 12" of steel and a 3" x 12" 2S aluminum five-step plate with the following step thicknesses: 1/16", 1/8", 1/4", 3/8" and 1/2". The sides of the explosive slab were confined with 1/4" x 1" x 12" steel plates to minimize any lateral expansion effects. Two 1/8" diameter holes were drilled through the aluminum plate 8 3/4" apart, so as to record the position of the detonation wave on a smear camera record. The first hole was 3" from the top of the plate and the other hole was 1/4" from the bottom of the plate. The distance between the three center steps was 1 3/4". The lowest step with the bottom hole was 2" long. A wooden baffle of 1/4" x 3/4" x 2" was glued to each step as indicated in Figure 1. Its purpose was to deflect the product gases from an explosive test pellet that might possibly obscure the detonation trace of the pellet below. A lucite flasher of 1/8" x 1/8" x 2" was attached to each step as indicated in Figure 1, in order to record the free surface motion and therefore give a reasonable check on the free surface velocity. The distance between the plate surface and lucite flasher for the 1/16", 1/8", 1/4", 3/8", and 1/2" step plates was respectively .010, .025, .032, .040, and .040 ± .0003 in. On each step of the plate, a square explosive pellet of 3/4" x 3/4" x 1/4" was centered on the face of the plate, glued along the sides, and covered with scotch tape to insure a sharp trace. The assembly was fired with a detonator inserted in the top of the 65/35 HMX/TNT slab, and the entire phenomenon was recorded with a rotating smear camera. Observation was made along the center line of the charge (center line of Figure 1a).

A similar explosive assembly was used to measure free surface velocity. These determinations gave a measure of the impacting shock strength in the explosive test. On each step of the aluminum plate, three pairs of lucite flashers of 1/8" x 1/8" x 2" were placed such that the

[1] J. M. Walsh and R. H. Christian, *Phys. Rev.*, Vol. 97, 1544 (1955)

first flasher was 1/4" from the foot of the step and separated from the adjacent flasher by 1/8". The distances between the 1/16" plate surface and lucite flasher pairs were .005, .010, and .015 ± .0003 in., while those for the 1/2" plate surface were .040, .055, and .070 ±.0003 in. All lucite flashers were spaced at distances within the double reflection time of the shock wave in the corresponding plate thickness.

RESULTS

Analysis of the Free Surface Velocity Record

The distance traveled by the detonation wave before it arrived at the first hole was sufficient to assume a steady velocity. As is shown in Figure 2, the upper and lower flashes are those due to the detonation wave sweeping by the holes to give a position and time in space. By drawing a line tangent to the two traces, a detonation velocity was determined for the donor explosive. The values are reported in Table 1. This in turn established the impact time for the detonation wave on the back side of the aluminum plate. Consequently, a zero time line was established for the shock wave in the plate. In addition, the three pairs of flashes at each plate thickness were recorded as the free surface impacted on the lucite flashers. The time between each pair of flashes was determined by simply measuring the distance along the time axis and converting it into time. The writing speed of the camera was 3.157 mm/μsec. The calculated velocities were plotted against the aluminum plate thickness and are shown in Figure 3.

As a consequence, a transit time for the shock in the aluminum at the specified thickness of the plate was then determined. Time intervals that corresponded to calculated free surface velocities and known lucite flasher distances from the plate surface at each plate thickness were subtracted from the recorded flash positions in time. This established the initial position of the free surface in time and therefore, a transit time for the shock in the plate. Consequently, a new position-time line was determined for each plate thickness to be used as the zero position-time line at the interface of the aluminum free surface and the explosive test pellet in the analysis to follow.

Analysis of the Test Pellet Record

A typical record is shown in Figure 4. It was prepared for analysis by projecting the image on a sheet of paper and drawing in the important features as indicated in Figure 5.

As described above, the zero position-time line for the shock at the interface of the aluminum pl and explosive test pellet was established. The earliest point in time, on the detonation trace, was then considered to be at the y coordinate corresponding to the point of initiation. The initiation was assumed to start at the explosive-metal interface. By assuming a radial expansion of the detonation wave as emanating from that point, time measurements along the pellet trace were related to distances which could easily be determined. Over the corresponding distances, a theoretical time was found to be constant for all points on the trace within the error of measurement. The point selected as center of initiation thus suggested itself as having physical reality and the determined difference in time was considered to be a measure of the delay time in initiation. In cases where the "hook" was not evident, a point along the y-axis was located which gave a constant delay time for all points on the trace. With the limited number of points (five for all except HMX/TNT and cyclotol, which had ten) a best straight line was drawn. The deviation of the points from the line was within .03 μsec. Graphs of free surface velocities versus delay time are given for all tested explosives except TNT in Figure 6. The results for TNT were scattered between 0.72 and 1.1 μsec. Shot data are given in Table 1.

DISCUSSION

As previously indicated, the results are given for a single shot record except for the two explosives 65/35 HMX/TNT and 75/25 cyclotol, which were fired in duplicate. The time spread for the duplicate shots was within .05 μsec. Similar spreads for the other explosives fired are expected when analysis is completed. However, the free surface velocity measurements and corresponding shock velocities which determine a transit shock time do not agree with the results of Walsh and Christian. By extrapolating their data to lower free surface velocities and using their corresponding shock velocities, a longer transit shock time was obtained. In Figure 6 the data thus obtained for 65/35 HMX/TNT are plotted in curve 5 for

comparison with curve 3. If the longer time is correct, the remaining curves would then be displaced by the same amount. Additional data will be obtained and results adjusted. The results will be published as a NAVORD Report.

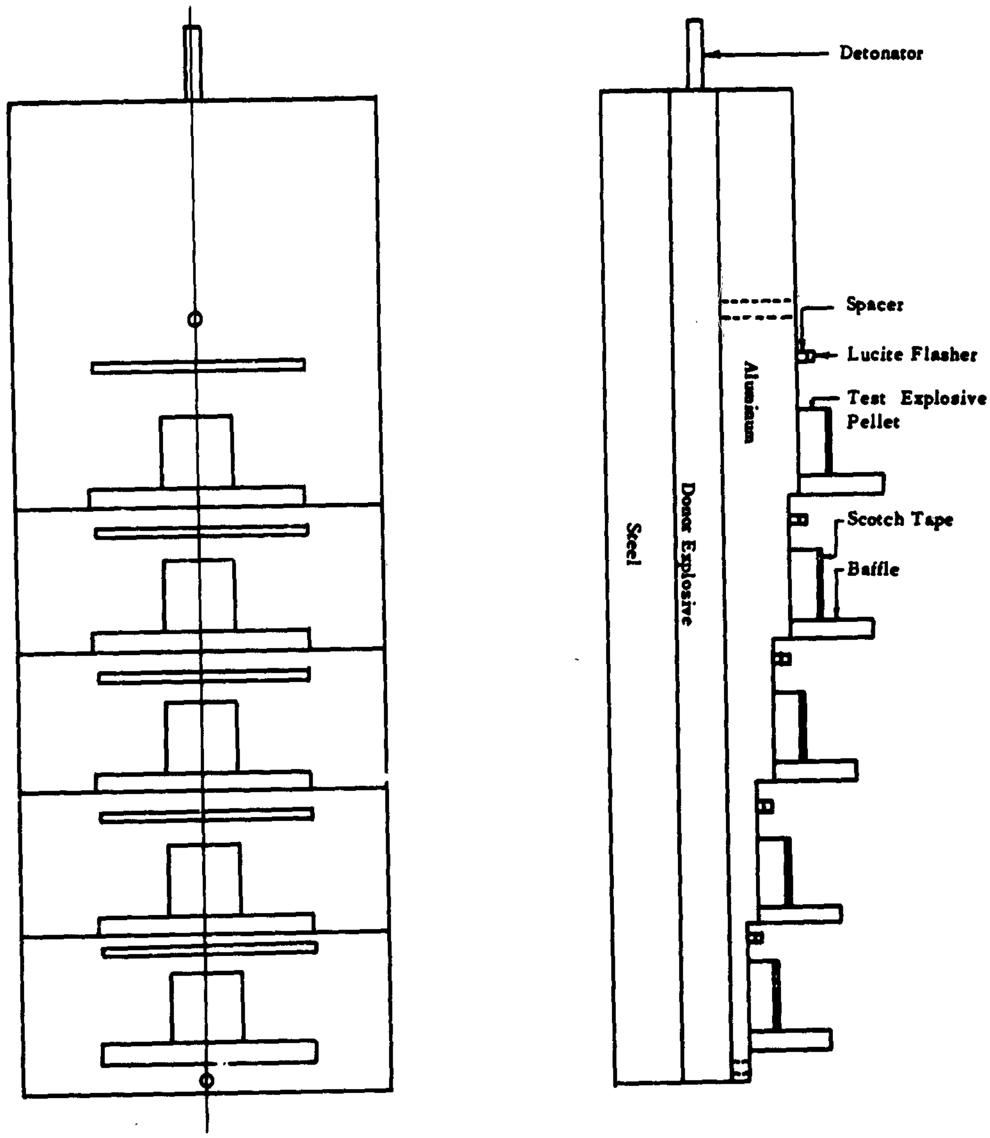
ACKNOWLEDGMENTS

I wish to thank Dr. Sigmund J. Jacobs for his valuable suggestions and discussions, and Mr. William Brown and Mr. Anthony Valenzino for carrying out the experimental work.

TABLE 1

Calculated Detonation Velocities

Shot No.	Density of Donor Slab (65/35 HMX/TNT), g/cc	Slab Thick. in.	Calc. Det. Velocity, mm/μsec	Explosive Pellet	Pellet Thick., in.	Pellet Density, g/cc	Det. Vel. Assumed (NOL), mm/μsec
3479	1.780	.399	8.150	75/25 Cyclotol	1/8	1.700	8.130
3498	1.770	.399	8.150	" "	1/4	1.700	8.130
3499	1.750	.400	8.050	HMX/TNT	1/4	1.750	8.170
3500	1.760	.400	8.110	Comp. B	1/4	1.680	7.940
3501	1.770	.400	8.050	TNT	1/4	1.540	6.750
3503	1.750	.400	8.040	50/50 Pentolite	1/4	1.670	7.620
3505	1.750	.400	8.040	65/35 HMX/TNT	1/4	1.750	8.170
3519	1.780	.402	8.150	Lucite Flashers			



Front View. Slit Plane Centered on Charge

Side View

Fig 1 Front and Side Views of Explosive Assembly

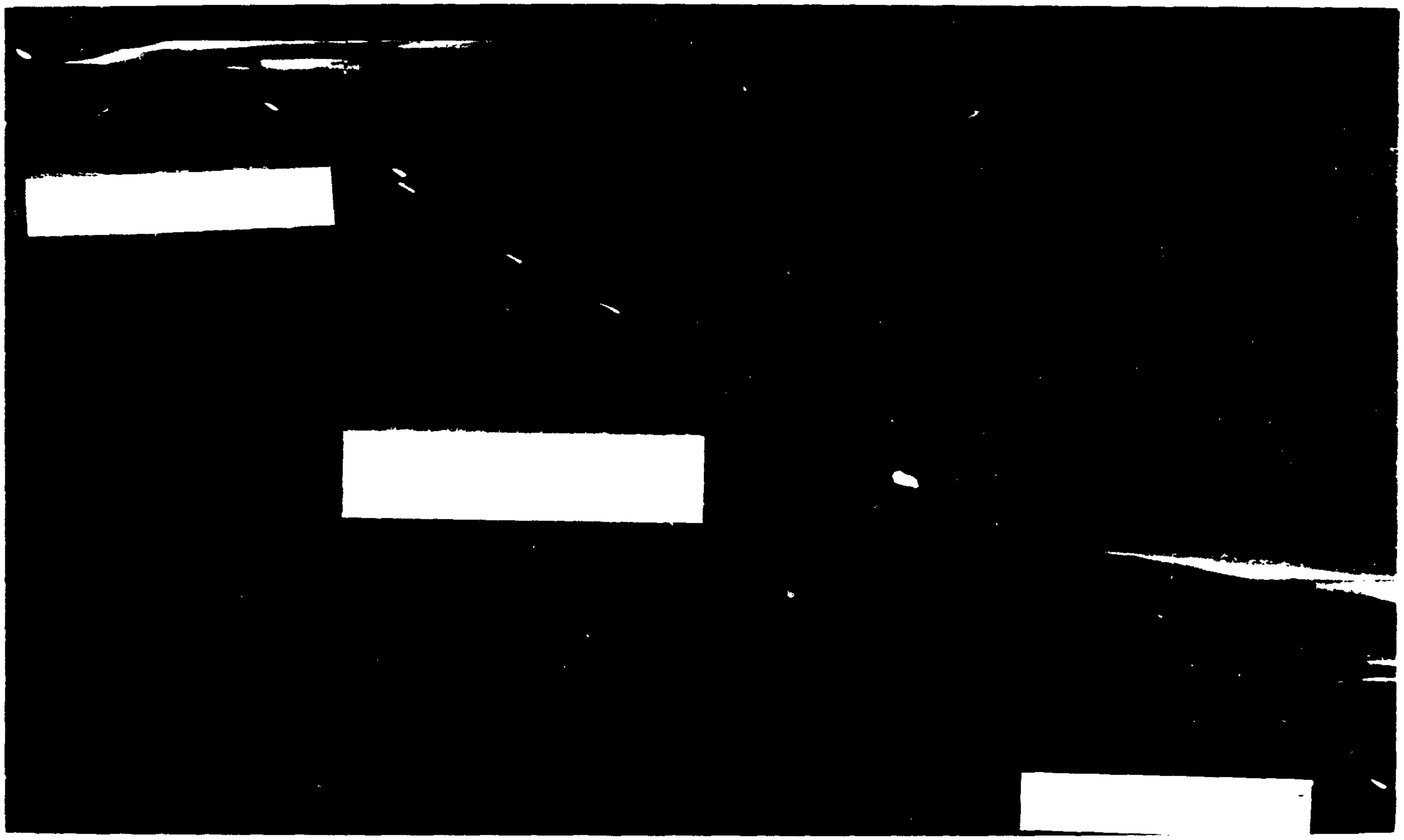


Figure 2

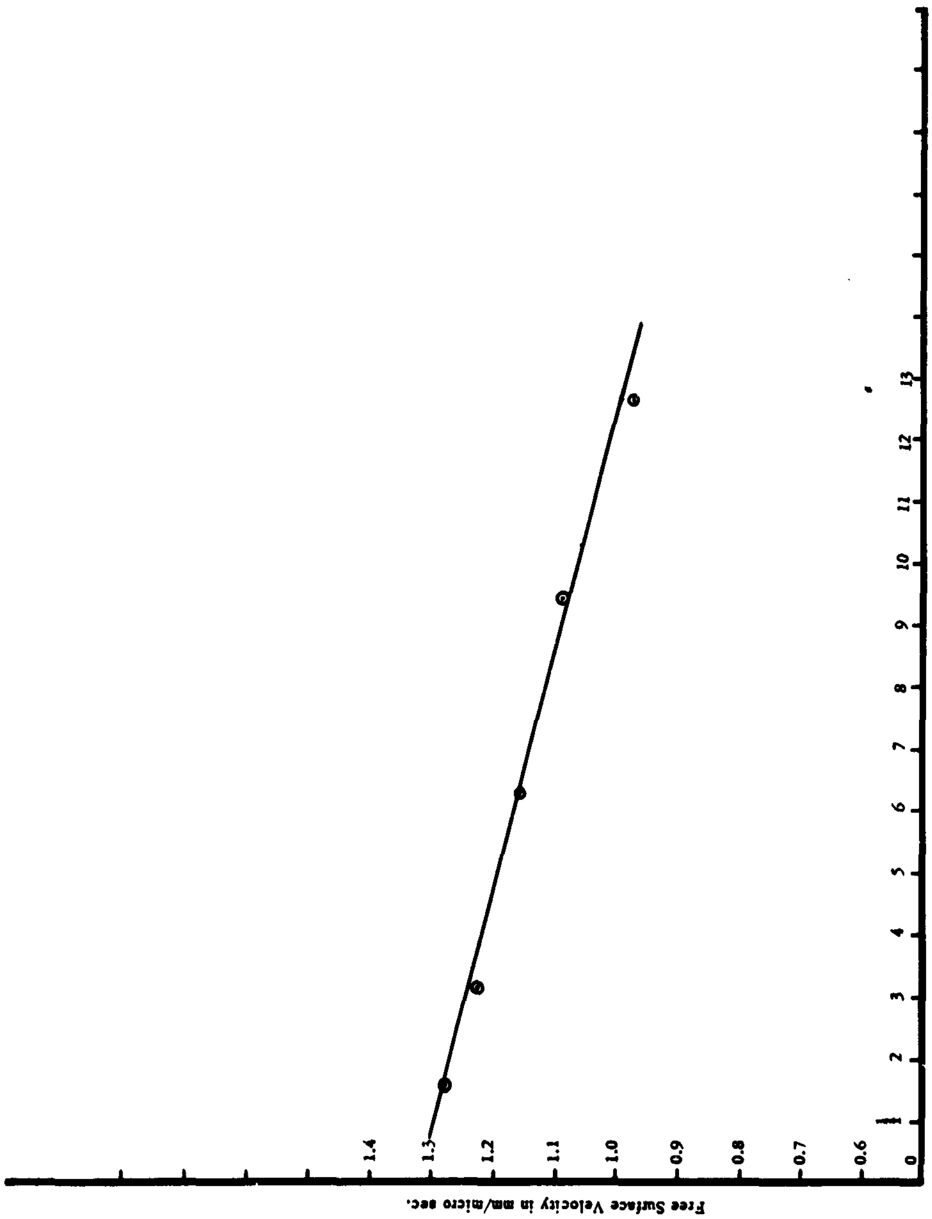


Fig 3 Aluminum Free Surface Velocity vs Thickness of Plate

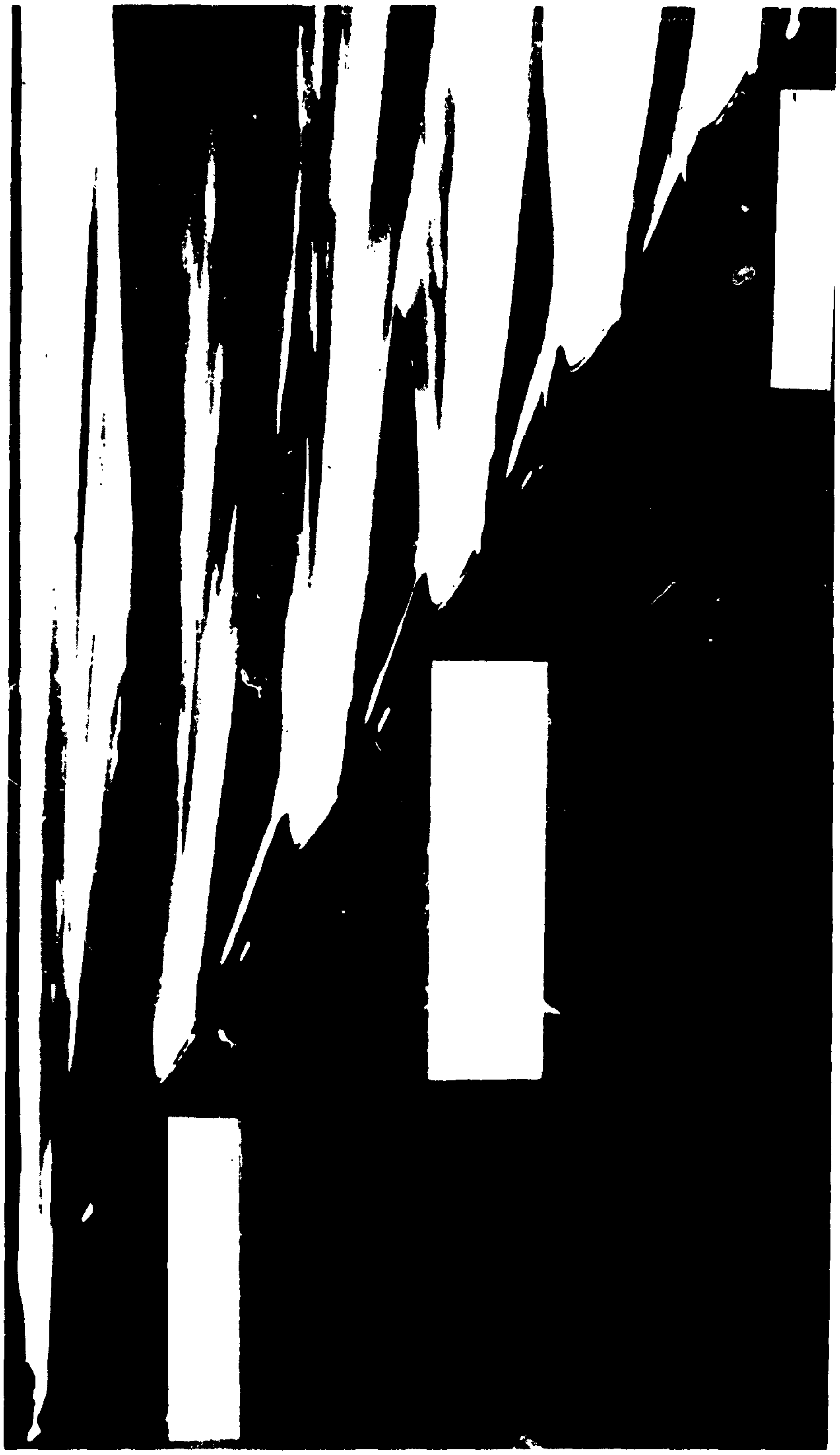


Figure 4

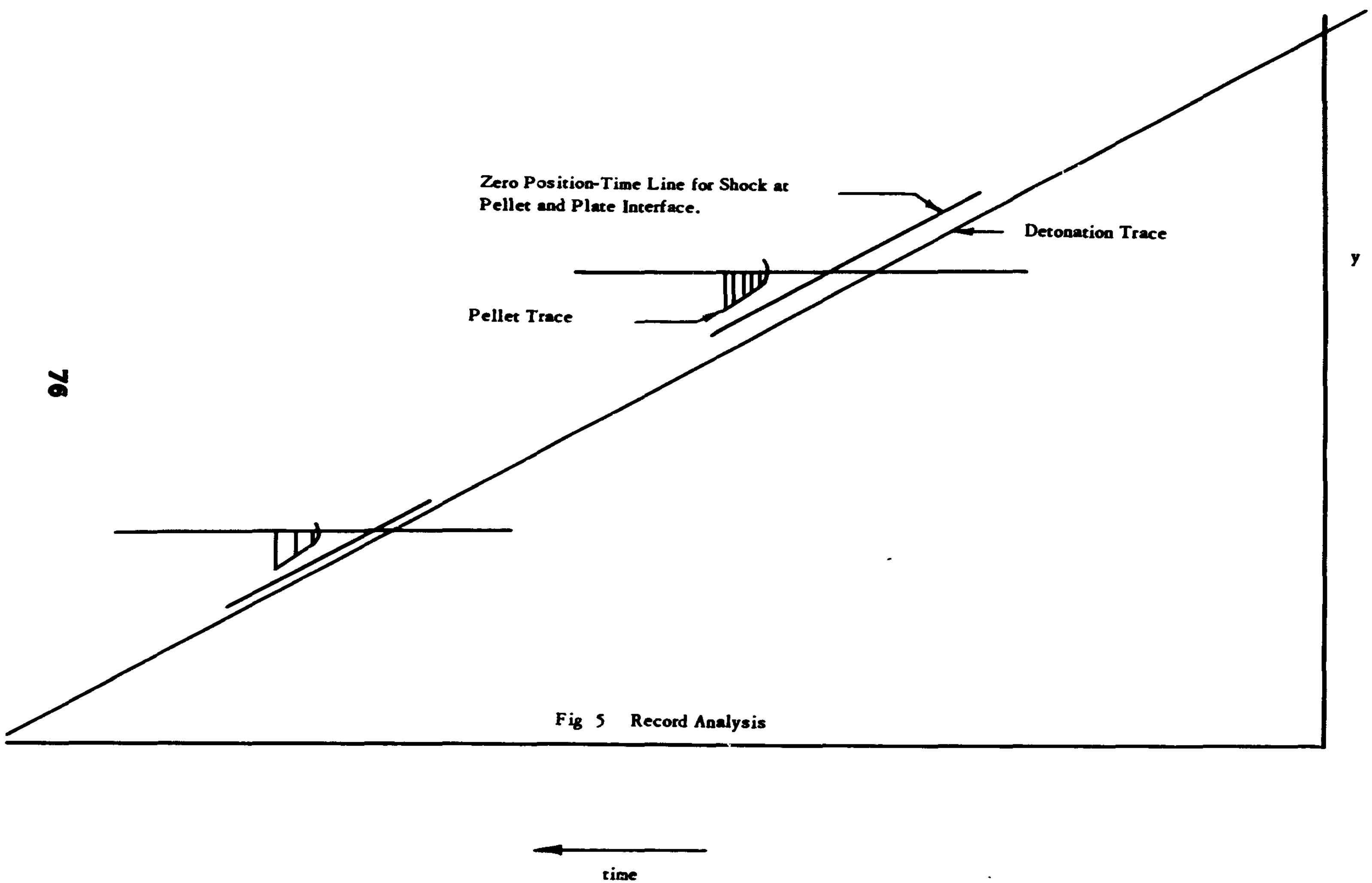


Fig 5   Record Analysis

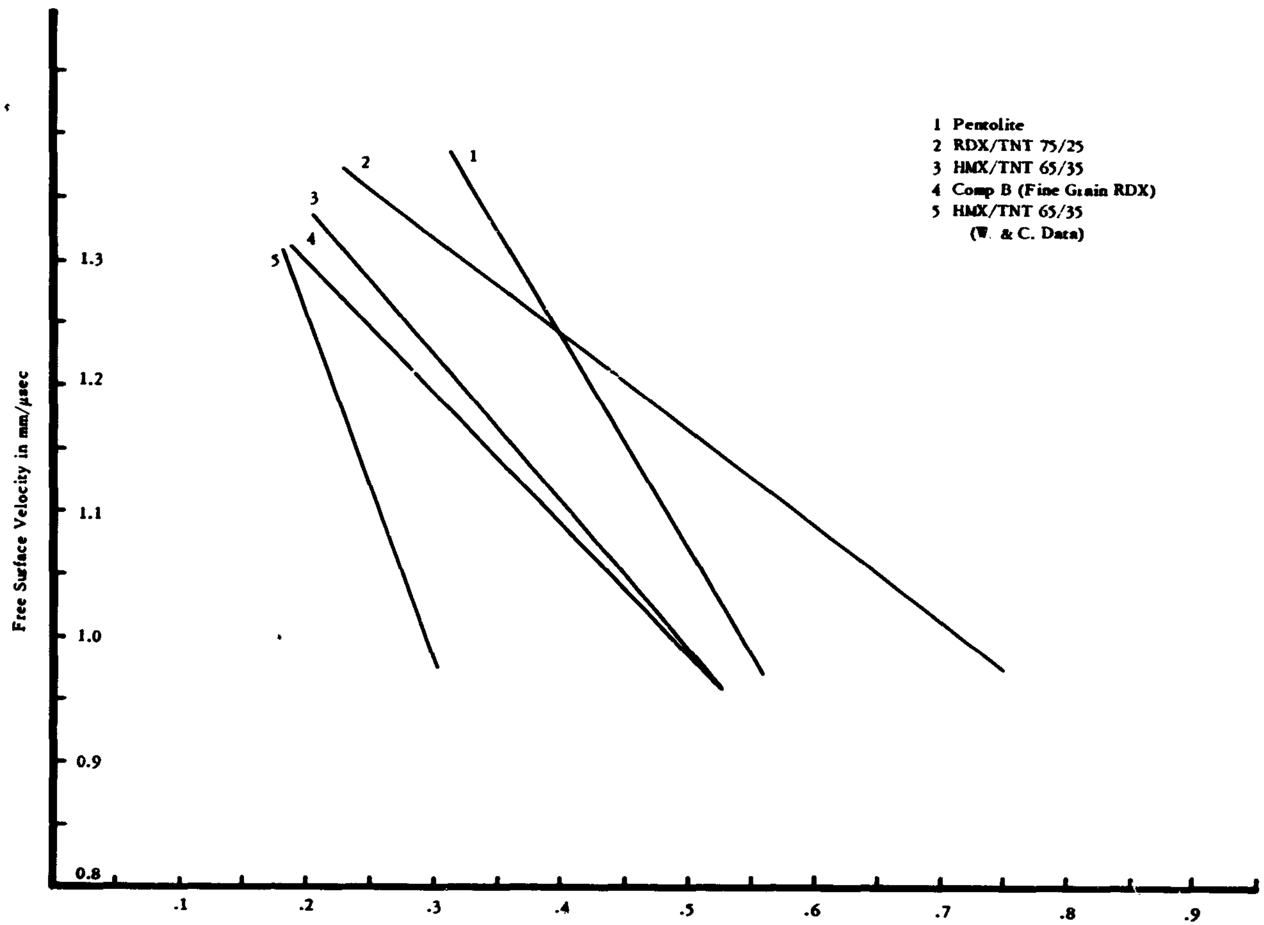


Fig 6 Aluminum Free Surface Velocity vs Delay Time

DESIGN OF A TWO-COMPONENT PLANE-WAVE LENS

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INTRODUCTION

Plane-wave explosive lenses of 4.0, 7.5, and 8.0 inches in diameter, for use by the Los Alamos Scientific Laboratory on research projects, were manufactured for a number of years in the Salt Wells Pilot Plant of the Naval Ordnance Test Station, China Lake, California. The slow component was made with baratol, and the fast component with Composition B. The original design, supplied by Los Alamos, assumed point initiation at the apex of a baratol cone. It was found that if the apex of the cone was rounded off, the planeness of the detonation wave emerging from the base of the slow component (that is, the degree to which it approaches a plane) could be improved to give a detonation front within 0.10 to 0.20 μsec, of the ideal. With good luck from compensating errors, even better results were sometimes obtained. To assure planeness within 0.10 μsec, it was necessary to consider the point of initiation at some place other than the apex of the slow component. Normally this center of initiation will be located within the detonator.

Obtaining a plane explosive wave involves more than a good design. It is necessary to reproduce explosive composition, density, and dimensions within close tolerances. But it is possible with skill in casting, and moderate care in reproducing dimensions, to manufacture lenses from baratol and Composition B which give detonation waves that do not deviate from the ideal plane wave perpendicular to the lens axis by more than .10 μsec. Planeness to within .01 μsec has been obtained but can not be assured for a given two-component lens made from Composition B and baratol.

The information presented here is based on work that was probably completed before the development of the air-cavity lens by Jacob and Liddiard.[1] I believe that the air-cavity lens, from the standpoint of

[1] S. J. Jacobs and T. P. Liddiard, *A New Plane Wave Booster*, Naval Ordnance Laboratory, White Oak, Maryland, Nav Ord Report 3620, 15 January 1954 (CONFIDENTIAL)

simplicity in fabrication, is a great improvement over the two-component explosive lens. Nevertheless, if there should be need for a two-component plane-wave lens, it may be helpful to have information on its design and characteristics. Two-component lenses should be structurally stronger than the air-cavity lens, and it may be easier to generate plane shock waves of large area with two-component lenses than with air-cavity lenses. The two-component lenses can be machined and fitted together to form large plane waves by simultaneous initiation of the lenses.

This paper presents the equation used to design the contour between the slow and fast explosive components, the procedures for making contour corrections, the major causes of deviation from planeness in lens performance, and briefly, some of the problems involved in the manufacture of a two-component, plane-wave lens.

EQUATION FOR PLANE-WAVE LENS CONTOUR

The lens may be represented as a body of revolution about the vertical axis ON shown in Figure 1. The area MNP contains the slow explosive, and the area outside the line MP contains the fast explosive.

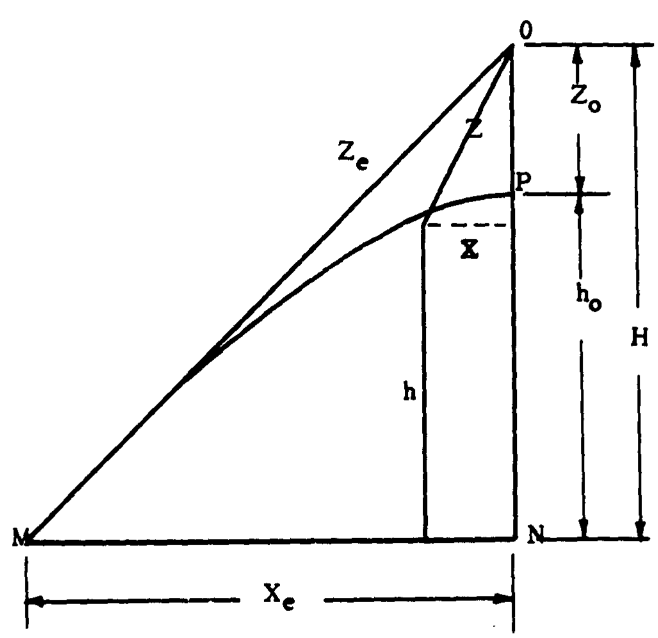

Fig 1

$$\frac{Z_e}{v_f} = \frac{Z}{v_f} + \frac{h}{v_s} = \frac{Z_o}{v_f} + \frac{h_o}{v_s} = t \tag{1}$$

t = transit time from initiation to emergence from the base of the slow component at MN

Z = path length in fast component

h = path length in slow component

v_f = detonation velocity of fast component

v_s = detonation velocity of slow component

A plane wave is generated when initiation starts at O, and when t is the same for all Z and h paths.

The index of the lens, n, is defined as

$$n = v_f/v_s$$

Then

$$t = (Z + nh)/v_f = (Z_o + nh_o)/v_f$$

Since

$$Z + nh = Z_o + nh_o$$

let this relationship be called K; then

$$Z = K - nh \tag{2}$$

From Figure 1 it can be seen that

$$Z^2 = X^2 + (H - h)^2$$

Substitute this value of Z^2 for Z^2 in the square of equation (2) and solve X^2; then

$$X^2 = (K - nh)^2 - (H-h)^2 \tag{3}$$

This equation is the equation for the contour of the lens. For the initial design, n can be determined from the linear velocity of the explosive components. Since $H = Z_o + nh_o$, H and K can be determined if Z_o and h_o are found. The exact value of Z_o is found by experimentation. A first approximation of Z_o is obtained by estimating the distance from the apparent center of detonation in the detonator to the apex of the slow component. To find h_o observe that in Figure 1

$$X_e^2 = Z_e^2 - H_e^2 = (Z_e - H)(Z_e + H)$$

and that

$$H = Z_o + h_o$$

Then, since

$$Z_e = Z_o + nh_o$$

it follows that

$$X_e^2 = (n - 1)\, h_o\, [2\, Z_o + (n + 1)\, h_o]$$

By rearranging terms

$$(n^2 - 1)\, h_o + 2\, (n - 1)\, Z_o h_o - X_e^2 = 0 \qquad (4)$$

The first design of a two-component, plane-wave lens is usually at best a close approximation and can be improved. It has not been found possible to determine the best value of H without experimentation, since the location of 0 is dependent on the characteristics of the detonatoı and since it may be shifted to compensate for composition variability of the slow component. If the apparent origin of initiation for the best design happens to be identical with an actual center of initiation, this can be regarded as purely accidental.

A number of factors may cause the first design to lack simultaneity

by more than a specified amount. Among these are the following: (1) the slow-component velocity is likely to be greater than linear velocity; (2) the fast-component velocity along the contour is less than linear velocity; (3) cast explosives are not uniform in composition; (4) during overcasting of baratol, dimensional changes are likely to occur; (5) casting or machining may not produce exact dimensions; and (6) the center of initiation selected for optimum design may be incorrect.

CORRECTION OF LENS DESIGN

When a new lens has been fabricated, it is necessary to evaluate its performance. This is done by means of a rotating-mirror camera. The camera views a narrow section passing through the center of the lens base and records the emergence of the detonation wave with respect to time and position. A composite trace is compiled and used for computing corrections. The Salt Wells Pilot Plant practice has been to use composite traces from at least 10 firings for final corrections.

Two methods of correction may be employed. The first appears the simpler of the two. From the composite trace, compute h coordinate corrections, using

$$\partial t/\partial h = \frac{1}{v_f}\left[\frac{(h - H)}{(Z)} + n\right] \tag{5}$$

derived from the basic equation $v_f t = Z + nh$, where v_f and n are assumed constant. The disadvantage of using only equation (5) for computing new h coordinates is that if used for successive corrections it is likely to produce a contour that can not be expressed mathematically. Further, it is difficult to apply a judgment factor based on the knowledge that a lagging portion of a wave tends to speed up and a leading portion of a detonation wave tends to slow down. Thus larger corrections are usually required for some portions of a lens than are indicated by the trace.

The second method of contour correction involves computation of corrected values of n, H, and K for equation (3). For the derivation below it is assumed that X_e, h_e, and the overall lens height remain constant.

In order to compute the correction for H, it is first necessary to differentiate equation (3). Substitute $K = H + (n - 1)\, h_o$ and assume that X is constant, thus:

$$\partial H = \frac{(H - h - nZ)\partial h + Z\,(h_o - h)\partial n + Z\,(n - 1)\partial h_o}{H - h - Z} \tag{6}$$

In order to solve for ∂n, form two equations, the first by substituting $h_e = h = 0$, $Z = Z_e$, and $\partial h = \partial h_e$ in equation (6), and the second by letting $h = h_m$, $Z = Z_m$, and $h = h_m$ in the same equation. Use these two equations to eliminate ∂H and then solve for ∂n. If point M in Figure 1 is used as the reference point--that is, the point of zero correction--then $\partial h_e = 0$, and

$$\partial n = \frac{A\,(H-h_m - nZ_m)\,\partial h_m + [(AZ_m - BZ_e)(n-1)]\,\partial h_o}{BZ_e h_o - AZ_m\,(h_o - h_m)} \tag{7}$$

where

$A = H - Z_e$

$B = H - h_m - Z_m$

Let

h_m correspond to h at $X_e/2$

Once ∂n has been calculated, it is possible to compute ∂H from equation (6) with $h = h_e$, $Z = Z_e$, and $\partial h_e = 0$. Then

$$\partial H = \frac{Z_e\,(h_o - h_e)\,\partial n + Z_e\,(n - 1)\,\partial h_o}{H - h_e - Z_e} \tag{8}$$

The above method of correction has been used with good results on an eight-inch, plane-wave lens. It is not necessary to have point M as the fixed reference when making corrections, but this has been found to be practical.

OTHER FACTORS CAUSING DEVIATION FROM PLANENESS

Desired results require not only a correct design but also good control of process variables. For example, a departure from design of ±.005 inch in the slow-component apex region will cause ±.01 μsec error in the detonation wave; and a departure of ±.003 inch at X = 4 inches will have a like effect.

Again, shifting the center of initiation off the axis has the effect shown in Figure 2. If the detonator is shifted off center to the left by .100 inch when viewed from the camera position, the wave observed with a rotating-mirror camera will appear about .25 μsec early on the left and about .25 μsec late on the right. In order to keep off-center initiation from producing an out-of-planeness of more than .01 μsec, it is necessary to hold centering tolerances to about .002 inch.

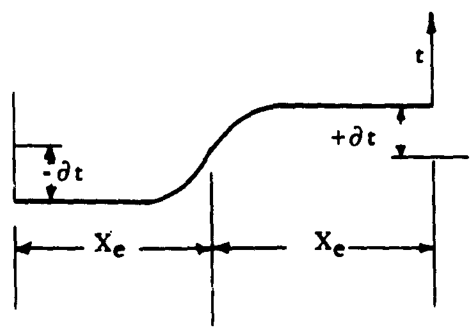

Fig 2

Again, slight changes in Composition B seem to have little effect on the wave shape, even when the transit time may be changed. However, inhomogeneity of the slow component can give a great amount of trouble if the inhomogeneity and composition variation occur near the base. Composition changes of the slow component apex region may have relatively little effect on the wave shape.

The most difficult component to hold constant is the baratol, because its high-density barium nitrate tends to settle rapidly during the casting process. TNT, because of impurities, tends to grow irreversibly; thus baratol density and dimensions change slightly during overcasting.

Barium nitrate must be entirely dry when added to TNT to make baratol; otherwise the resulting castings will not be alike in their inhomogeneities. It is also necessary to control barium nitrate particle size in order to control viscosity of baratol melts and settling of barium nitrate during the casting cycle. Accurate weighing of TNT and barium nitrate is necessary for accurate control of composition.

Although fairly close tolerances can be maintained, it can be seen that combined effects of all variables can soon make it difficult to hold the lens performance within a range of .10 μsec.

SUMMARY

To sum up. This paper has presented a lens design, methods of correcting it, and some of the problems involved in the fabrication of two-component lenses. Average data from a large number of lenses show that the design method here described can define a contour for a two-component lens within .01μsec. Individual lenses, because of inadequate process control, do not match this performance.

For those who want to take the trouble to do so, it is possible to produce individual lenses from fast and slow explosives that will generate a plane wave within 0.10 μsec and with reproducibility within .05 μsec. Best results are achieved when the trouble is taken to make precise shapes, to control properties of raw materials, to reproduce particle size of crystalline material, to control and reproduce all process conditions, and to get operators to follow instructions exactly.

It may be added that more detailed information regarding plane-wave lenses than that given here may be obtained from the Explosives Division of the U. S. Naval Ordnance Test Station. Similar information may be obtained elsewhere--but perhaps not so easily.

EXPLOSIVE WAVE SHAPING

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ABSTRACT

Peripheral initiation of pentolite charges was employed in an attempt to generate a conically collapsing detonation wave to be used in shaped charge studies. Failure of this technique to produce the desired wave form required extension of the program to include wave shaping by delayed detonation through tapered steel spacers, a technique which proved successful in producing the desired detonation wave shape.

INTRODUCTION

This paper was written specifically as a brief review of the work associated with, and leading up to wave shaping in explosives carried on at these Laboratories at different periods during the past six years. Results of both unpublished and previously published work in this field, as presented at the first Symposium on Detonation Wave Shaping sponsored by Picatinny Arsenal at the Jet Propulsion Laboratory, on 5 - 7 June 1956, are included.

The dependence of shaped charge performance on the configuration of the detonation wave used to collapse conical liners has been studied by many investigators. The most common form of shaping used has generally been designed to produce plane, hemispherical, or trumpet bell forms.

This investigation was conducted to establish a charge configuration which would produce a conically collapsing detonation front to impinge simultaneously upon, and in a direction normal to the entire conical wall in a standard shaped charge liner.

Wave shapes resulting from charges designed by simple geometric techniques similar to those reported by other investigators were analyzed and used as a basis for this study. Data on delayed initiation through steel, which is the subject of a forthcoming Ballistic Research Laboratories report, gave the quantitative information used to design the final charges described in this report.

EXPERIMENTAL PROCEDURE

Charges

All of the charges were cast 50/50 pentolite and were arranged for the two types of peripheral initiation as shown in Figures 1 and 2. To obtain the desired geometry of initiation, barriers of lead oxide powder were used as shown. In the phase of wave shaping through steel delay spacers, the charge was cast directly on the steel.

Instrumentation

The shape of the waves emerging from the test charges was examined by "emergence" recording with the streak rotating-mirror camera (Ref 1). In the peripherally initiated charges the length of the main explosive column was varied over the range indicated in Figures 1 and 2 so that both position and time analysis could be made of the charging wave shape.

In the studies of the delay of initiation through steel, two-dimensional models were photographed simultaneously with the streak rotating-mirror camera and Faraday shutter (Ref 2). The fixed time-space records of the Faraday shutter were then used as a check of the correction applied (described under "Data Reduction") for the distortion in time which is a characteristic of the streak rotating-mirror camera records.

PHASES OF STUDY

Peripheral Initiation

Two types of peripheral initiation were tested. The first, shown in Figure 1 was designed geometrically to produce the wave indicated under the corresponding "geometrical constructions." The second design (Fig 2) which is more nearly exact peripheral initiation, would be expected to produce the wave shape indicated. After testing these two shaping initiators it became obvious that the desired conical form could not be obtained with these configurations.

Delay Through Air Gap

As a result of tests of sympathetic detonation reported earlier (Ref 3), the feasibility of delaying the initiation of an explosive receptor by varying

transit time of the shock from an explosive donor charge for various-width air gaps was investigated. As observed in this earlier study the time to initiation from the donor charge (Fig 3) consisted of two components, first the actual transit time in air, t_a, and secondly the travel time t_t, to the actual initiation which first appeared well beyond the face of the receptor charge. This additional delay in the explosive stick also added a distance component, d, which had to be accounted for in the design of an explosive wave shaper. Figure 4 is a composite print of twenty-five successive frames from the high-speed rotating-mirror framing camera (Ref 4), and shows the delay time and distance described above. These frames, printed in the form of a motion picture, which qualitatively present a more vivid description of this phenomenon, were prepared and presented at the Wave Shaping Symposium.

The results of firings for delay to initiation across an air gap indicated a "zone" effect (Ref 3) which made this application to controlled time delay wave shaping impractical.

Parallel Steel Spacers

The transmission of shock and consequent initiation through metal barriers placed between two charges, (Fig 5) has been extensively studied and will be described in detail in a forthcoming report. However, since this technique was the basis for the final wave shaping design, it will be covered briefly.

The detonation wave impinging on a steel block produced a time delay, to emergence of shock, which was found to be linear with steel thickness. The detonation in the second stick appears very similar to the initiation across air gaps in that the first emergence occurs well inside of the second stick, producing added delays in time and distance, similar to that observed in the air gap. However the total time to initiation was linear with steel spacer thickness.

A method for building this metal barrier configuration into a "three-dimensional" variable steel barrier charge was not apparent, but the linearity of delay through steel was adopted in the final design as described in the following paragraphs.

Perpendicular Steel Spacers

A donor and receptor charge were arranged on a steel plate as shown in Figure 6. The detonation wave in the donor charge travels perpendicularly to the face of the steel plate, setting up the shock which is transferred to the receptor charge. The series of two successive front-lighted Kerr-Cell exposures (Fig 6) clearly show the shock in the donor and the detonation emerging well inside the donor along this line of shock.

High-speed rotating-mirror framing-camera records were taken of this initiation through varying thicknesses of steel. The wave shape and time delays produced are shown in Figure 7. The framing-camera records (Fig 8), which were prepared in movie form for presentation at the Wave Shaping Symposium, show that the initiation starts at the shock front in the receptor and propagates along that line as well as radially from the point of initiation, thus producing a wave which is tipped with respect to the axis of the receptor charge. This tipped front plus the incorporation of the linear time dependence on spacer thickness were considered in the final design of the wave shaper developed to produce a conically collapsing detonation wave.

Tapered Steel Spacers

The information obtained from streak-camera records (Fig 7), framing-camera records, and single-frame exposures was employed in arriving at the tapered spacer design. In this design (Fig 9), as the detonation front in the donor moves along the face of the steel wedge from the thick to the thin end, the point of initiation in the receptor varies in both distance and time from the explosive-steel interface. The point of initiation is farthest from the interface at the thickest spacer width and at the interface at the thin end. Thus, by varying the length of the spacer, the angle of the detonation wave in the receptor can be varied over a considerable range.

a. Two-dimensional studies

Figure 9 shows the first two-dimensional design of a wave shaper, which, based on the results of the initiation through steel, was expected to produce a plane wave traveling at an angle to the explosive-steel interface. The actual wave which resulted indicated that a simple geometrical

design based on the earlier observations was not adequate.

After this charge was tested, corrections for the physical events which produced results contrary to the simple geometric analysis were incorporated in the design of the succeeding two-dimensional models. The final two-dimensional design shown in Figure 10 produced a satisfactory wave shape.

b. Three-dimensional studies

The features of this acceptable shaper were then incorporated in a solid (three-dimensional) model which was generated as a cylindrical charge by the rotation of the plane of symmetry of the two-dimensional charge through 360° around a center line which was expected to be the altitude of the final conical wave. Upon testing, this design failed to produce the geometrically anticipated wave (Fig 11), and the physical events which were observed to have led to this descrepancy were considered and compensated for in the final design of the three-dimensional charge shown in Figure 12.

REDUCTION OF DATA

All quantitative data obtained in these studies resulted from measurement and analysis of photographic records obtained with the streak rotating-mirror camera. Since these quantitative data were obtained from the streak rotating-mirror camera records, the wave shapes observed in emergence recording had to be time-compensated to correct the varying-time fixed-space traces to true space configurations.

In order to make the correction for time-distortion of the wave the assumption had to be made that the detonation wave traveled at constant velocity and that its direction of propagation was always normal to the front at every point. In the first types of shapers tested some error is introduced in the analyses of the wave shape because of the Mach interaction of the colliding wave fronts which produce higher than normal detonation velocity, but this error is not carried over into the final design in which all interaction of the collapsing wave is eliminated by barrier materials.

A first analysis of the shape of the detonation wave was made by geometrical construction of velocity vectors erected normal to the photgraphed

shape. The extrapolation back along these vectors for the distance compensating for the time interval to arrival at the emergence point of the wave moving at normal detonation velocity produced a first correction in which the velocity vector was not now necessarily normally directed from the corrected detonation front. Trial and error corrections were then made by redirecting the velocity vector at an angle which produced the proper time correction from the corrected front to the originally recorded front.

For a more direct correction of the time distortion in the final design, in which the necessary condition that the detonation wave traveled at a constant established velocity is true throughout the entire reaction, the following mathematical analysis, prepared by Mr. J. E. Shaw of this Laboratory, was applied to the data obtained from the streak rotating-mirror camera records of emergence.

The Determination of the Shape of a Detonation Wave from Slit Camera Record

Suppose a converging wave in a cylindrical stick of explosive, the camera looks at the end of the stick with the slit along a diameter and records the time of emergence of the various elements of the wave.

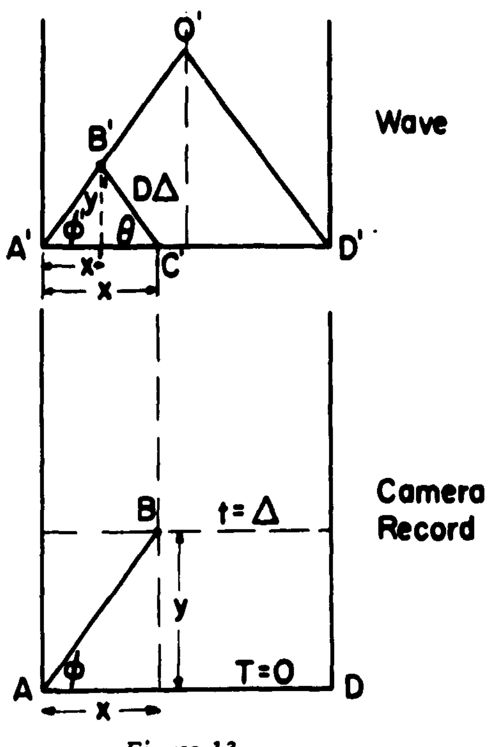

Figure 13

For the simple case let the wave shape be conical. $A'D'$ is the end of the stick and $A'O'D'$ is the wave, B' being any point in the wave. The direction of propagation of B' is along $B'C' \perp$ the surface of the wave. Let the time be zero when the first elements of the wave emerge from the end of the stick and let the time be Δ when the point B' emerges at C'. Then

$$B'C' = D\Delta$$

where the detonation velocity, D, may be assumed the same as for a plane wave. It is hoped that this will be a good approximation.

In the camera record the emergence of B' at C' will be recorded as point B.

Given point B in the camera record, the problem then is to locate the corresponding point B′ in the wave front.

From the camera record we measure coordinates x and y. We know the film speed, S, and detonation velocity, D. Unit magnification is assumed, or else that the coordinates and film speed are corrected for magnification. From the figure

$$\sin\phi' = \frac{D\Delta}{x} \qquad \Delta = \frac{y}{s} \qquad \theta = \frac{\pi}{2} - \phi'$$

$\sin\phi' = \dfrac{Dy}{Sx}$ from which ϕ' is determined.

$$y' = D\Delta\sin\theta = D\Delta\cos\phi' = \frac{Dy}{S}\cos\phi' = x\sin\phi'\cos\phi'$$

$$= \frac{Dy}{S}\sqrt{1-\left(\frac{Dy}{Sx}\right)^2}$$

$$x' = y'\cot\phi' = \frac{Dy}{S}\cos\phi'\cot\phi' = x\cos^2\phi' = x\left[1-\left(\frac{Dy}{Sx}\right)^2\right]$$

For the general case the tangent to the wave profile does not pass through A′. Then one more piece of information must be obtained from the films. The only other information obtainable is the slope of the curve.

Let δS be an element of arc of the wave profile making angle ϕ with the horizontal axis.

$\delta t = \dfrac{\delta y}{s}$ where S is the film speed, and t is time.

$$\sin\phi = \frac{D\delta t}{\delta x} = \frac{D}{S}\frac{\delta y}{\delta x} = \frac{D}{S}\tan\theta$$

where $\lim\limits_{\delta S\to 0}\dfrac{\delta y}{\delta x} = \dfrac{dy}{dx} = \tan\theta =$ slope of curve on film.

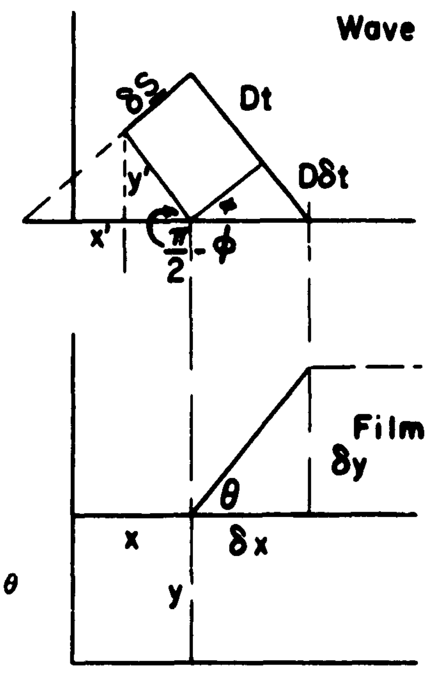

Figure 14

$$x - x' = Dt \cos\left(\frac{\pi}{2} - \phi\right) = Dt \sin\phi$$
$$= D\frac{y}{S} \sin\phi = \frac{D^2}{S^2}\, y \tan\theta$$

$$x' = x - \frac{D^2}{S^2}\, y \tan\theta$$

$$y' = Dt \sin\left(\frac{\pi}{2} - \phi\right) = Dt \cos\phi = D\frac{y}{S}\sqrt{1 - \sin^2\phi}$$
$$= D\frac{y}{S}\sqrt{1 - D^2/S^2 \tan^2\theta}$$

$$y' = \frac{Dy}{S^2}\sqrt{S^2 - D^2 \tan^2\theta}$$

For $\tan\theta = \frac{y}{x}$, these equations reduce to the ones for the conical shape.

It should be noted that where the wave is converging rapidly the velocity of propagation is increased so that the above assumption of D for the velocity of the wave is no longer valid. If we knew the velocity we could determine the shape but since the velocity depends on the shape we cannot get a solution by any simple method. If the end of the charge is at CC′, the wave front AOA′ is undetermined. Actually it is nearly flat. Shaped (concave) waves flatten out if the stick is sufficiently long.

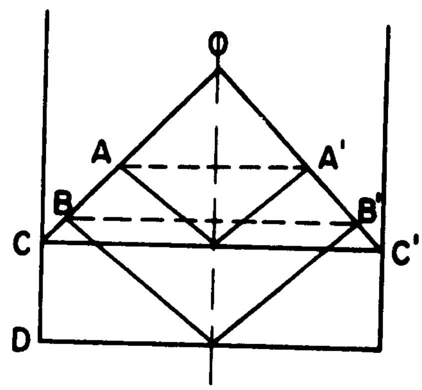

Figure 15

RESULTS

The delay time to initiation in a pentolite receptor charge by a pentolite donor separated by barriers of air or steel is a function of both the shock transit time through the barrier plus a delay to initiation in the explosive. The receptor charge does not initiate at the barrier-explosive interface but at a point inside of the receptor. With air gaps, the delay time was not a reliable function of gap size, while in steel the delay time was found to be linearly variable with barrier thickness.

By using variable delay as obtained through a tapered steel barrier, a plane detonation wave, tipped with respect to the explosive-steel interface,

was obtained from a detonation wave in the donor charge perpendicular to its interface.

Using the technique of a tapered steel barrier, a conically collapsing detonation wave was obtained.

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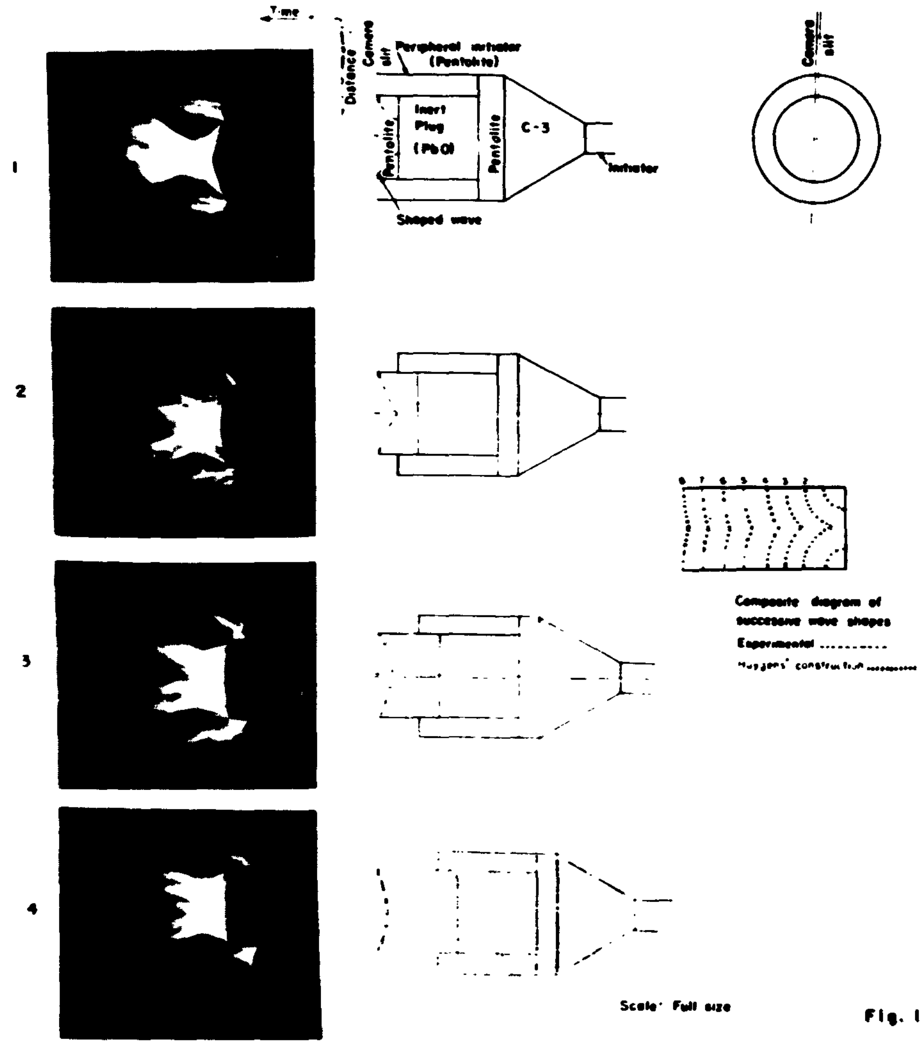


Fig. 1

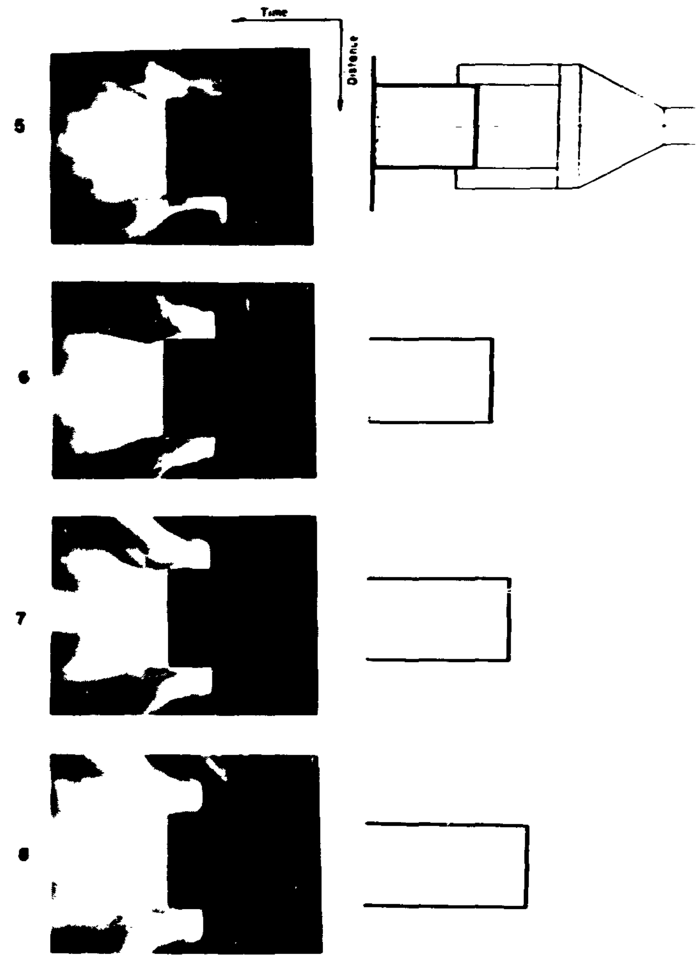


Fig 1A-

Fig 1 Successive Emergence Streak-Camera Records of Peripheral Initiation Showing Comparison of Wave Shapes

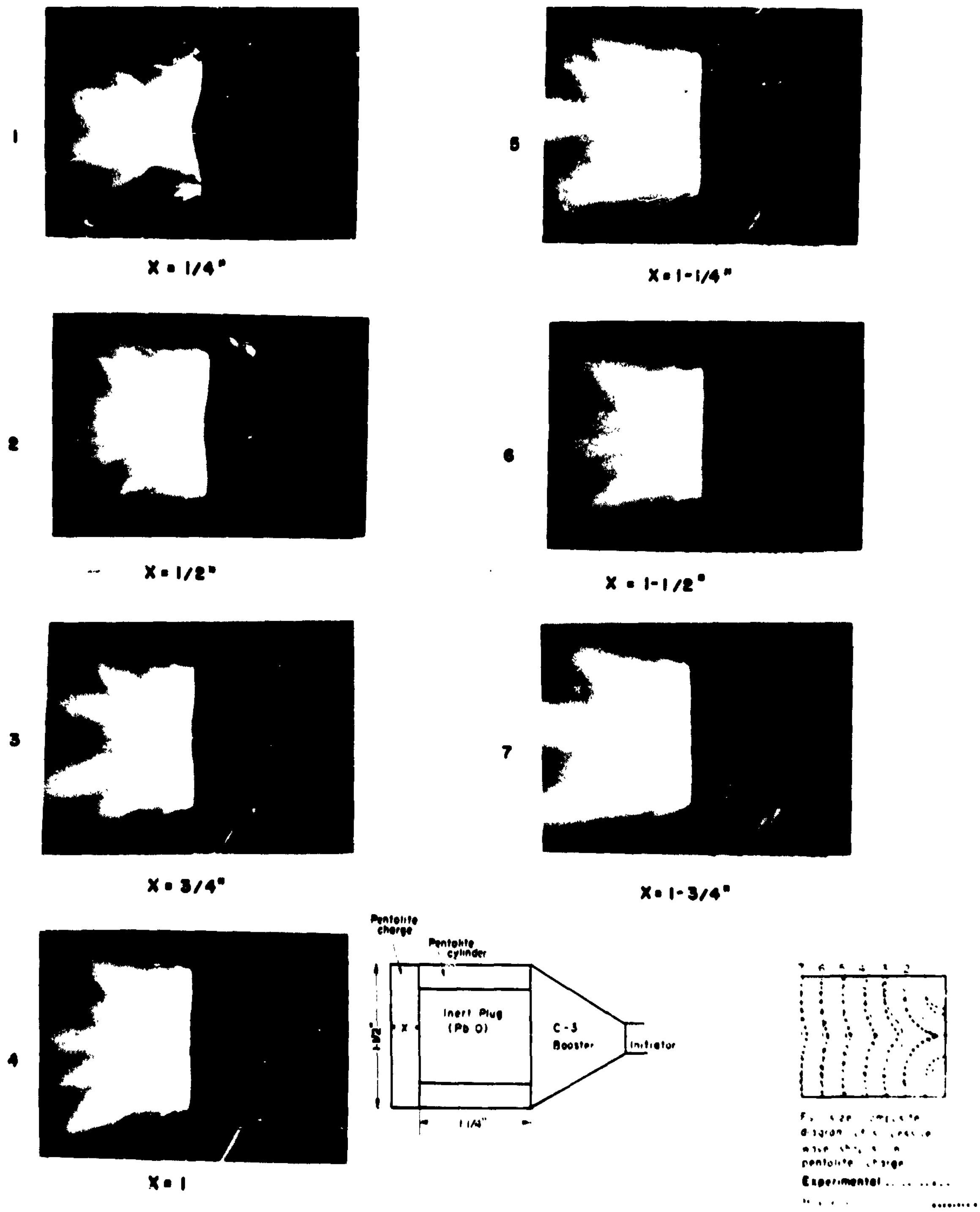


Fig 2 Successive Emergence Streak-Camera Records of Peripheral Initiation Showing Comparison of Wave Shapes

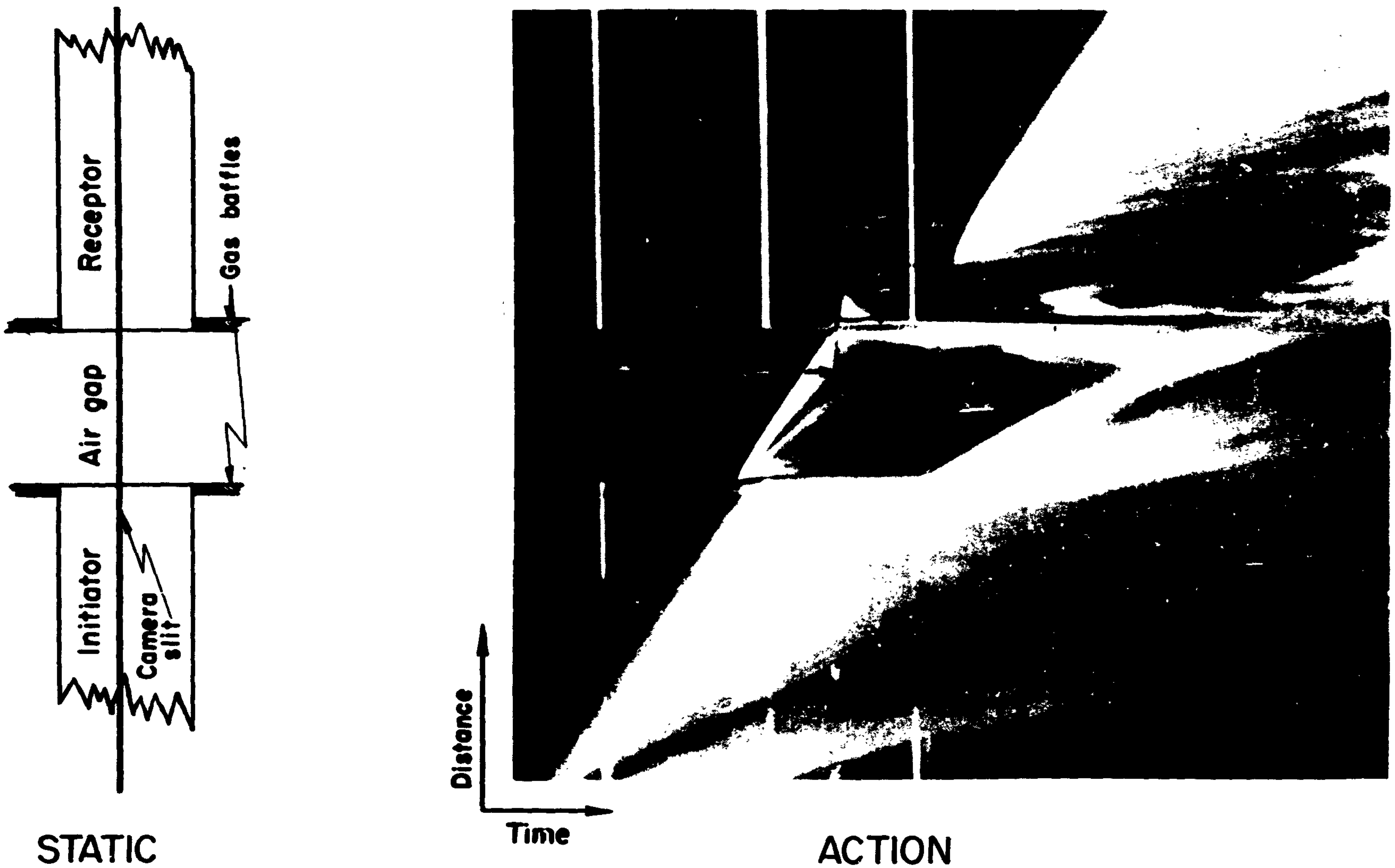


Fig 3 Rotating-Mirror Camera Record of Initiation of an Explosive Receptor by the Air Shock from an Explosive Initiator

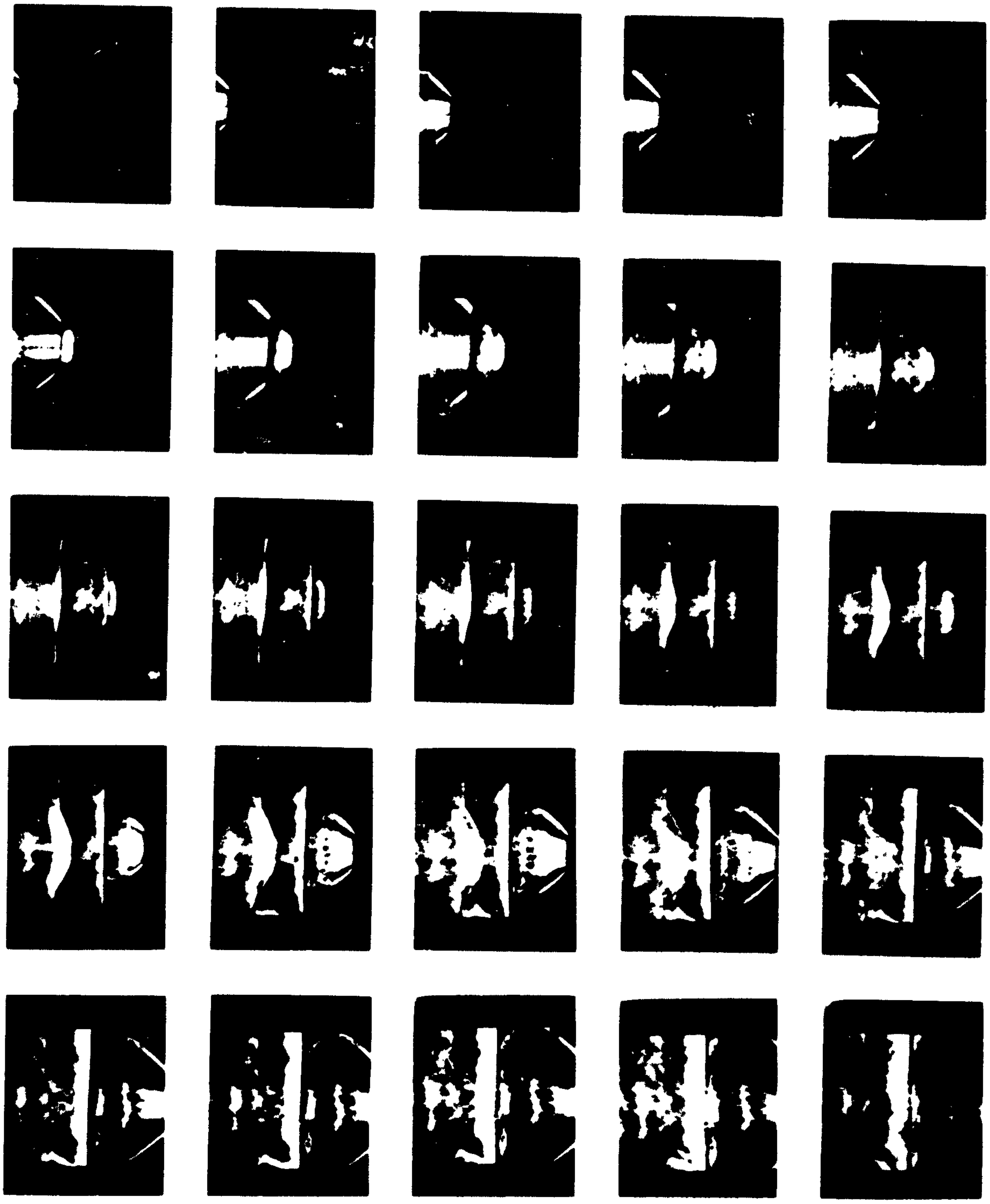


Fig 4 Twenty-five Successive Framing-Camera Exposures of Initiation across an Air Gap

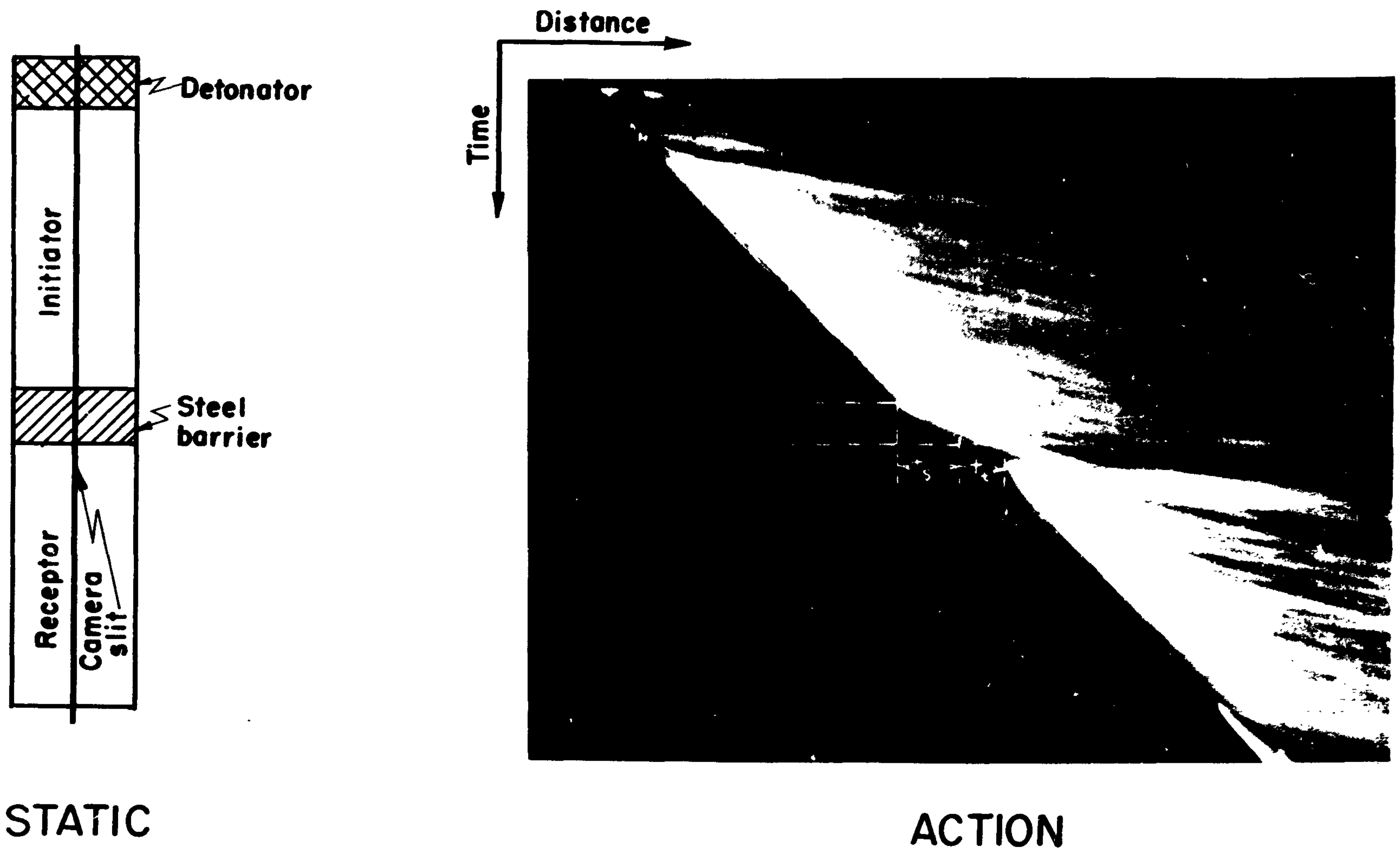
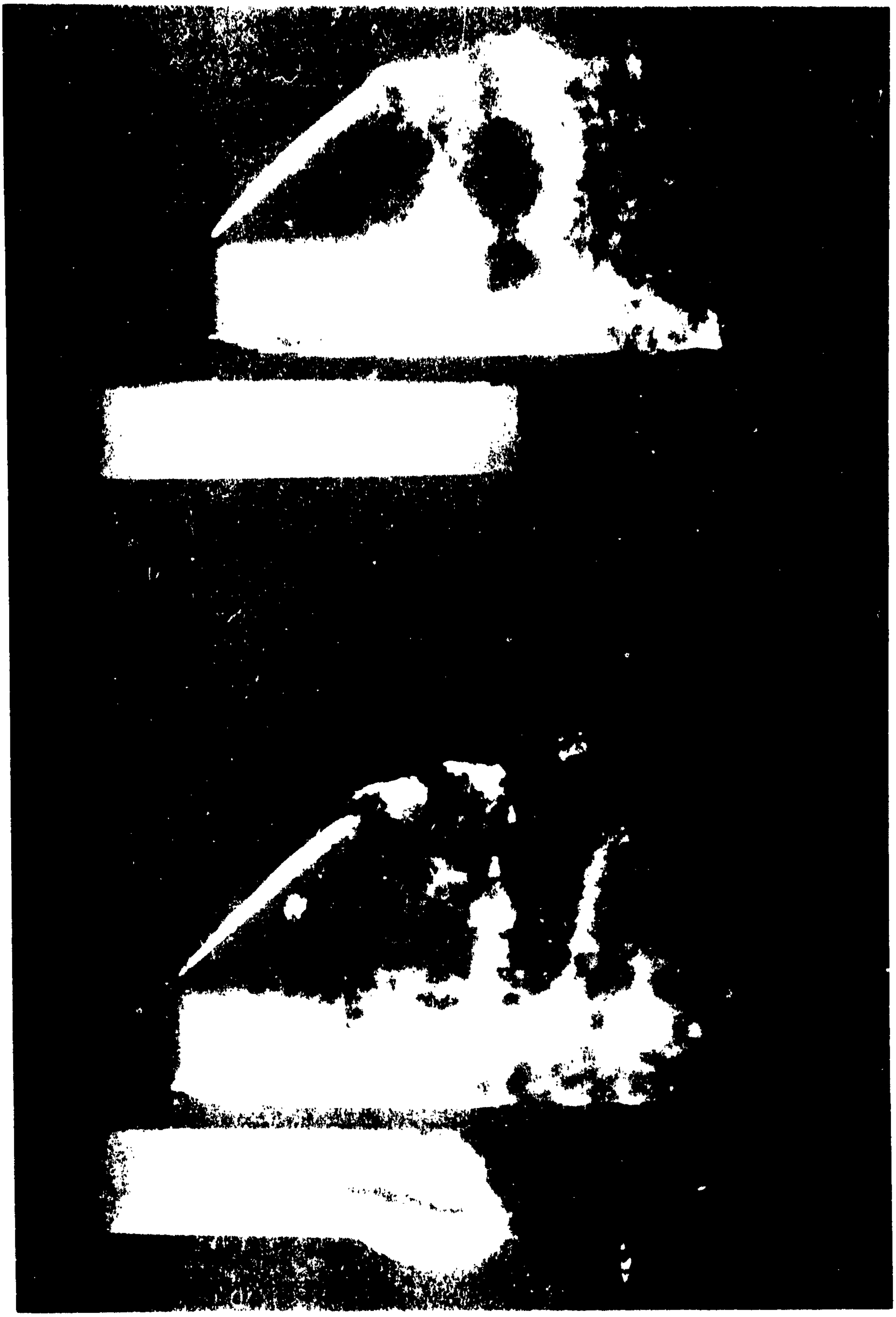


Fig 5 Streak Rotating-Mirror Camera Record of Initiation of a Receptor Charge by the Shock, through Steel, Set Up by a Donor Charge



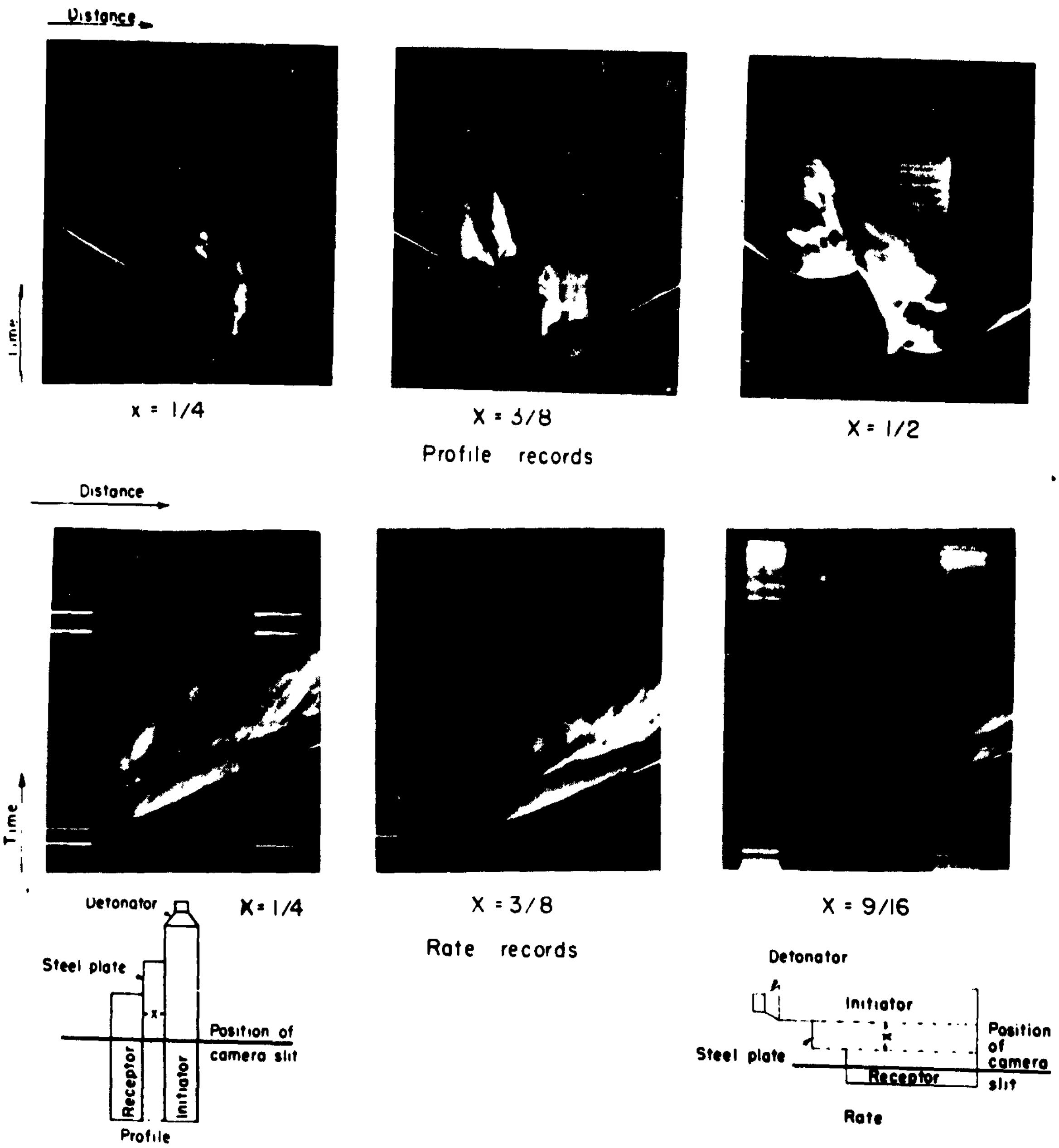


Fig 7 Examples of Rate and Profile Streak-Camera Records of Initiation through Steel Barriers

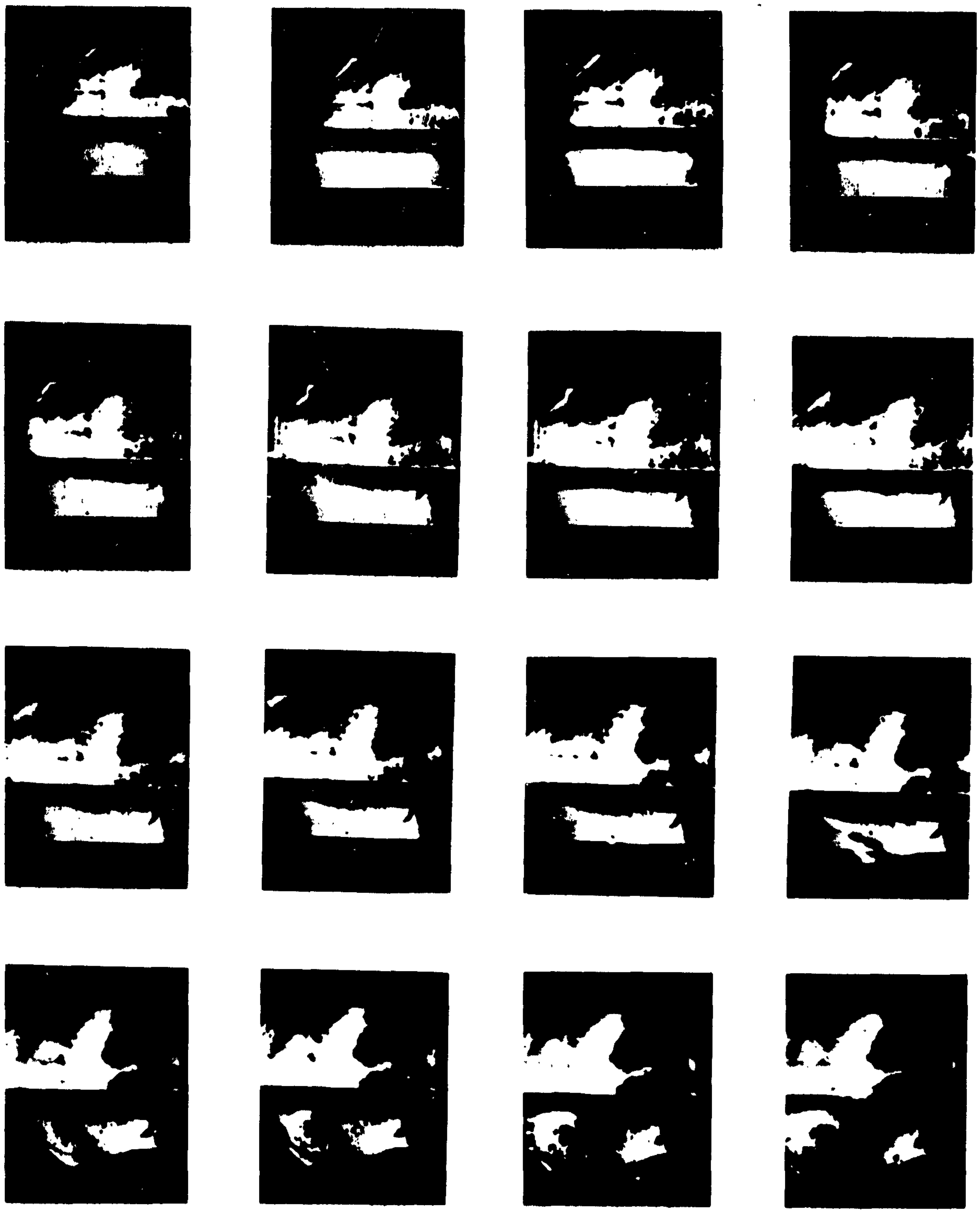
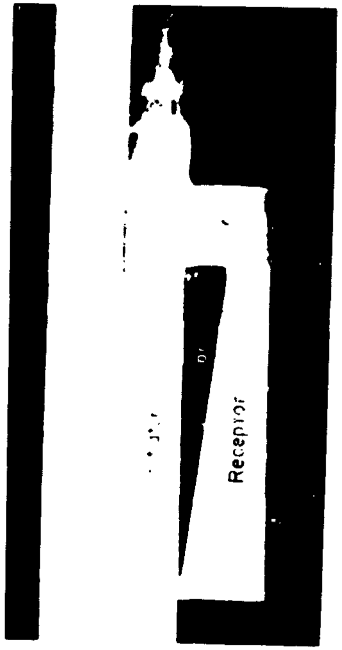


Fig 8 Consecutive Frames Taken at 0.8 μsec Intervals of the Initiation of a Receptor Charge through a Steel Barrier

Faraday, Shutter Exposure



Before Firing

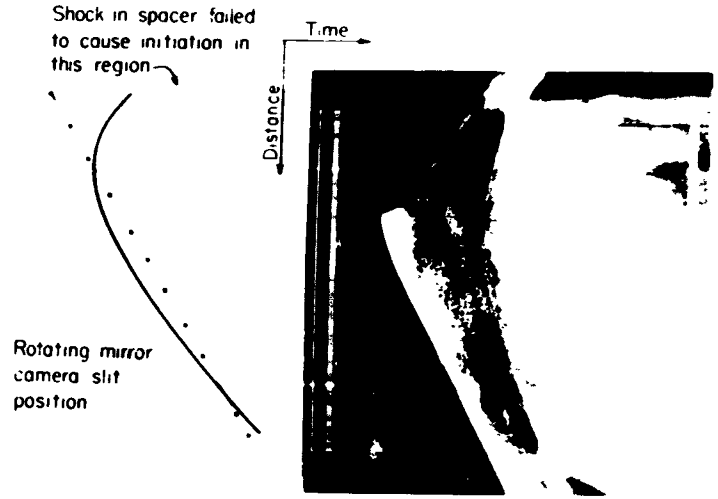


Fig 9 Wave Obtained with "Two-Dimensional" Tapered Steel Barrier

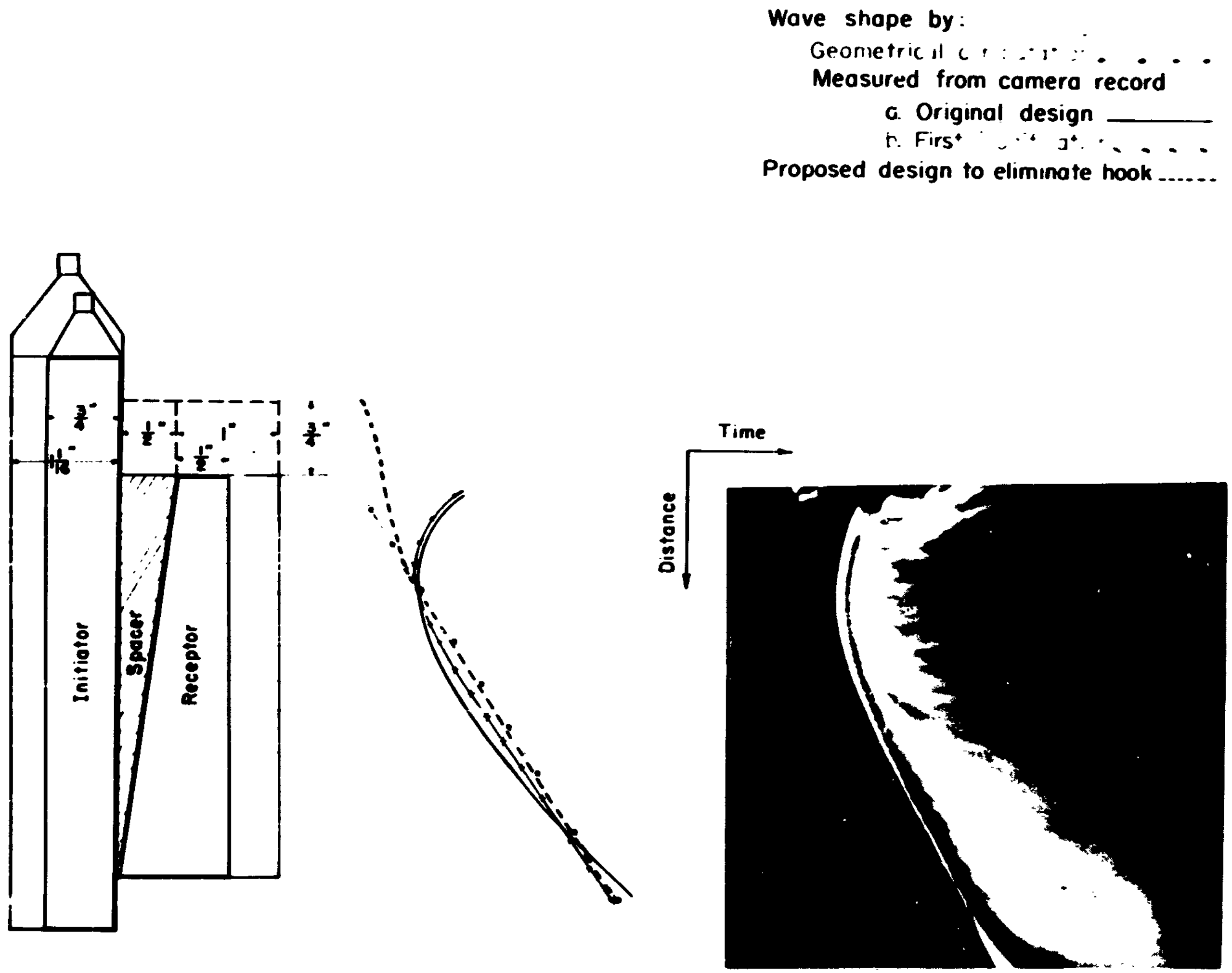


Fig. a. First modification

Fig 10 Wave Shapes Obtained from Streak-Camera Emergence Records of Modified Two-Dimensional Tapered Steel Barrier Shapers

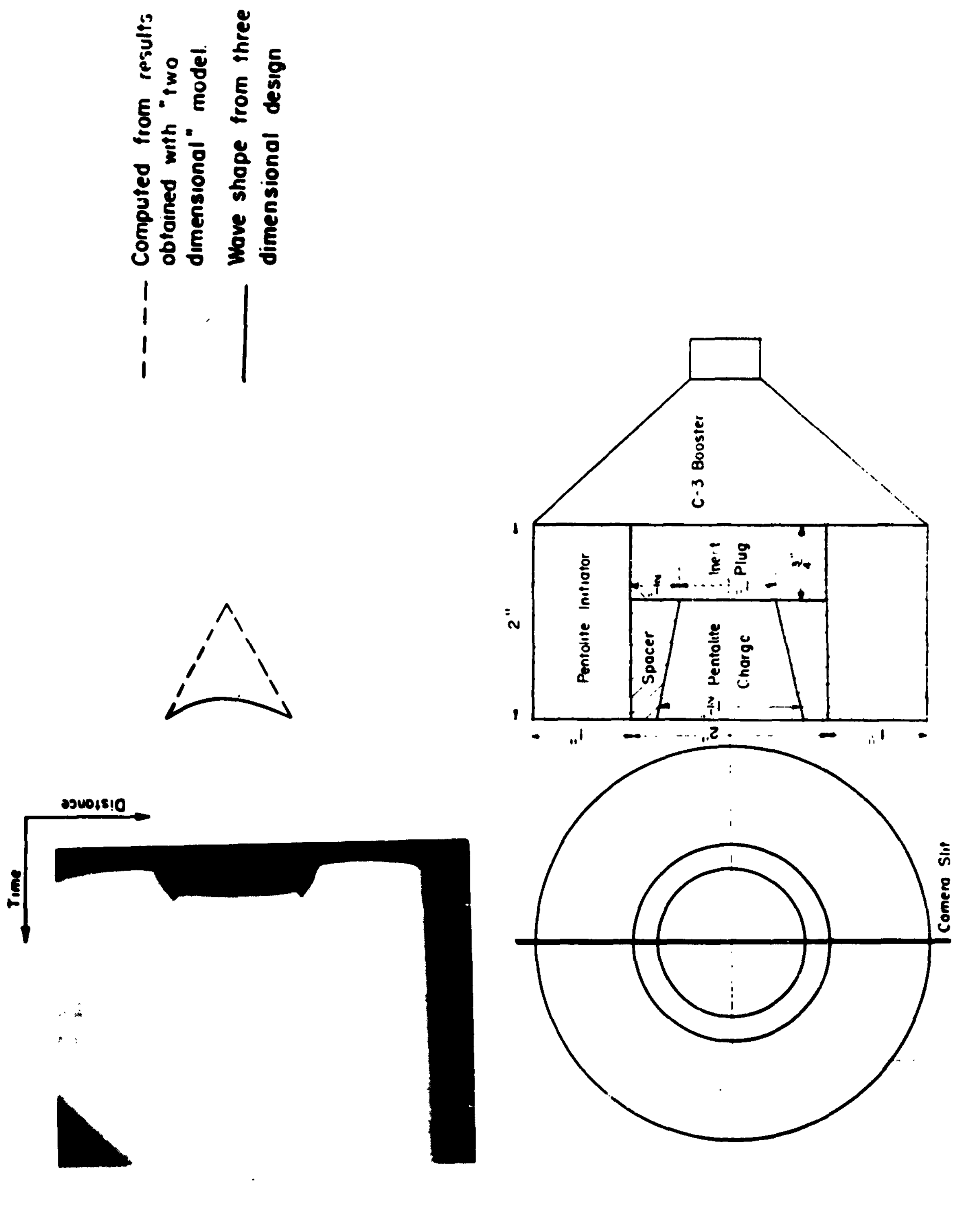


Fig 11 Streak-Camera Emergence Record of Wave Shape from Geometrically Designed Three-Dimensional Shaper Employing the Principle of Tapered Steel Spacers

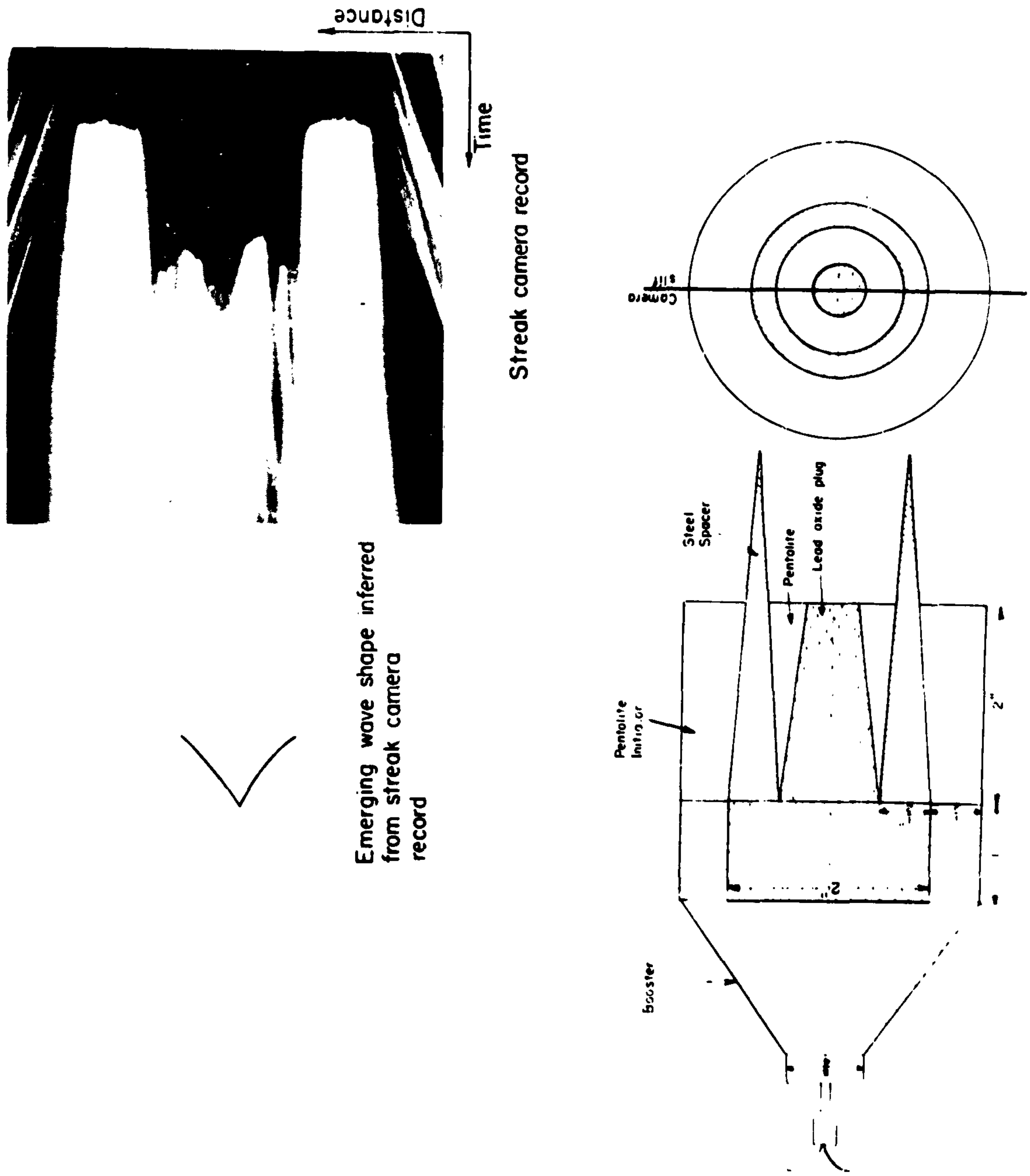


Fig 12 Final Design Employing Tapered Steel Barriers to Generate a Conically Collapsing Detonation Wave Shape

DEVELOPMENT OF AN AXIAL INITIATOR FOR THE PRODUCTION OF A CYLINDRICAL WAVE[1]

Melvin A. Cook and W. O. Ursenbach

University of Utah

ABSTRACT

The development of a device to produce a cylindrical wave is described which embodies the fundamental principles of wave shaping discussed by M. A. Cook in a previous paper (Ref 1). This initiator consists of a double-tapered steel core loaded with cast 50/50 pentolite and fitted with an M36 detonator, an air gap, and a double-tapered 61 ST aluminum sleeve. A 1/2 in. layer of tetryl ($\rho_1 \doteq 1.0$) surrounds the sleeve. Overall length of the initiator is 16 in., maximum diameter including the layer of tetryl is 3 in. This initiator has been used in testing both shaped-charge and continuous-rod warheads with satisfactory results.

The successful use of a shaped-charge liner in any weapon depends largely upon the symmetry of the impinging wave. An asymmetric wave will generally result in reduced jet formation coupled with unfavorable directional effects. Detonation of a central booster located in a warhead gives rise to a spherically expanding wave. Therefore, a cone, for example, at the periphery of the warhead, on a line perpendicular to the axis of the warhead at the booster, would be collapsed by a symmetrical wave (Fig 1). All other cones on the periphery would be collapsed by asymmetric waves, with a resulting possibility that jet formation and direction toward the target would be poor. A similar situation would exist for any warhead or cylindrical multiple-shaped charge device. If, on the other hand, means could be provided to furnish a cylindrical wave, all the cones would be collapsed properly and the jets arising therefrom would be directed toward the target (Fig 2). This paper describes a 16 in. axial initiator which has developed for use in a shaped-charge warhead for the Terrier missile.

[1] Work reported in this paper was carried out under Contract N123-60530S-1978A, Naval Ordnance Test Station, and under Contract N7-onr-45107, Office of Naval Research through funds from the Navy Bureau of Ordnance.

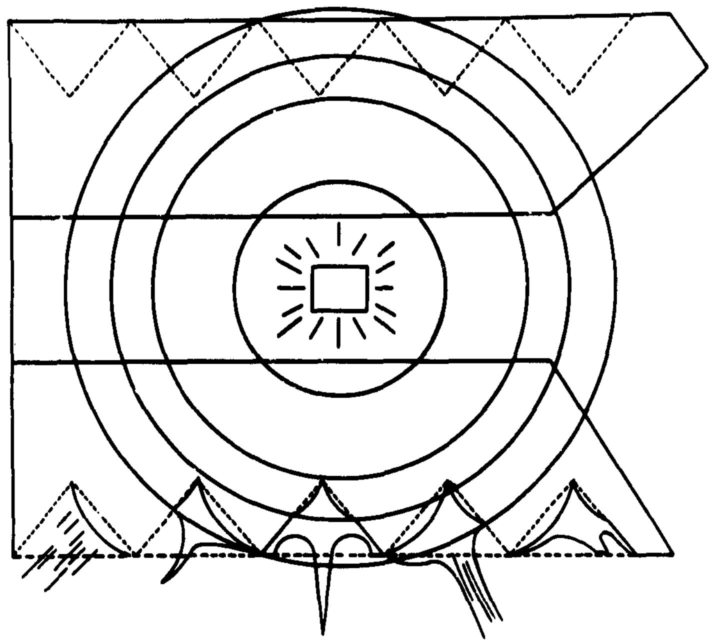


Fig 1 Function of a Multiple-Shaped Charge Warhead with Central Initiation

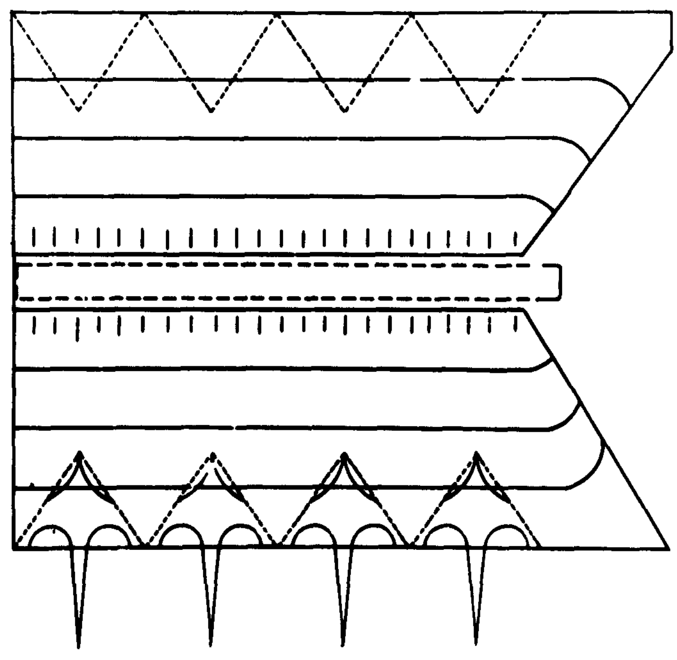
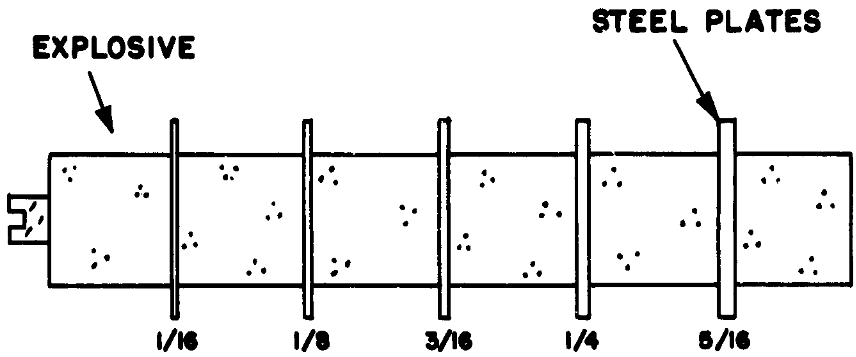


Fig 2 Function of a Multiple-Shaped Charge Warhead with Cylindrical Initiation

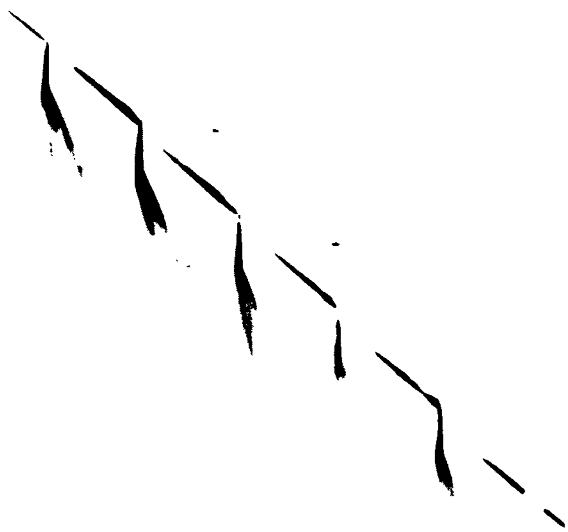
There are various schemes by which a cylindrical wave may be produced. However, most schemes proposed to date involved the use of a series of detonations extending along the axis of the charge (Ref 2), or of a single long detonator which might be fired along its entire length within 1 μsec. Such schemes invariably required high voltages not generally available in missiles or other weapons, or else the material involved is too sensitive to find satisfactory application in a service device. Even if such voltages were available and a sensitive explosive could be tolerated (such as a mixture of lead azide and silver powder), it is doubtful that uniform initiation could be obtained in a sufficient length to be usable. Experiments were conducted at this laboratory using a .0015 in.-diameter silver bridge wire 16 in. long and a firing unit of 0.2 μfd at 40,000 volts. Streak camera photographs of these tests indicated that the breakdown occurred essentially at a scattered few points rather than over the entire length. It would be difficult, obviously, to duplicate these conditions in a guided missile.

One other scheme of interest remains for our study. If a detonation occurring at the end or center of a missile could be delayed laterally in some fashion as it progresses along the axis of the charge, it is conceivable that a cylindrical wave might be generated. This paper discusses the development of such a device.

Previous studies have been conducted at this laboratory on the delay of initiation imposed by a barrier of steel placed between charges perpendicular to the axis of the charge (Fig 3; Ref 3). In this manner, delays in the direction of propagation as high as eight μsec were imposed in the detonation of the explosive. This information was later used in the development of means of shaping the detonation wave in the direction of propagation as reported by Cook, *et. al.* (Ref 4). In the particular case under study, delays were desired laterally rather than in the direction of the wave. Since effects along the side of a cylindrical charge are in general much less severe than in the direction of propagation, it was felt that delays as great as 40 μsec might be possible laterally from a detonating core of explosives. Thus a charge according to Figure 4 was prepared to determine the lateral delay through a metal of various thicknesses.



a. Diagram of Charge Prepared for firing



b. Rotating-Mirror Streak Camera Photograph of Detonation of(a)

Fig 3 Delay of Detonation of Explosive by Steel Plates

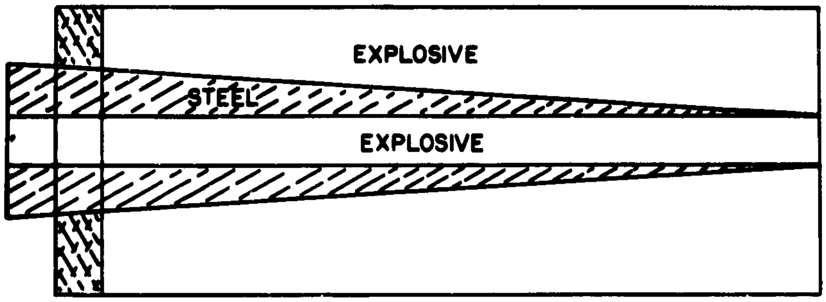


Fig 4 Typical Charge for Determination of Lateral Delay of Initiation

Several rounds were fired using steel elements with various degrees of taper, the bore varying from 0.5 to 1.0 inch, and maximum wall thickness varying from 0.25 to 0.50 inch. In all cases the explosive used was composition B, initiated at the base end with a 1" × 1" pressed tetryl booster. Photographs were taken with a rotating-mirror streak camera using a writing speed of 1.9 mm/μsec. These results were very interesting in that there were definite evidences of simultaneous initiation along some portions of the charge. However, these charges appeared to detonate over only a small portion, at the most approximately 50%. At this point, experimentation was changed to the rotating-mirror framing camera in order to determine the fate of the remaining 50% of the charge.

A tapered steel element similar to the one used in the above experiments with composition B loading was detonated with a 20-gm tetryl booster, and illuminated with an argon-explosive flash bomb. The event was photographed at a framing rate of 660,000 frames/sec. These pictures (Fig 5) showed that motion of the metal follows detonation of the explosive core with a delay of not over one μsec. Further, the apparent velocity of the metal at the base was 700 m/sec. During the desired 35-μsec delay of the detonation between the initiation end and terminal end of the charge, this metal moved approximately 2.5 cm, and therefore during this time interval explosives surrounding such an element could be physically broken without detonation. Subsequent photographs taken at this laboratory have shown that such a phenomenon did indeed take place. Rotating-mirror framing camera pictures have been obtained showing movement and fracture of explosive surrounding a metal-encased core

of explosive, such as that used in these studies.

It would appear that the problem of the damaging of explosive might be avoided in three ways:

1 Encase the entire charge in a confining core.

2 Use a loose-packed, low-density explosive to surround the core, since this material would only compress without breaking.

3 Provide sufficient air space to permit the expanding sleeve and detonation products to become cylindrical in the hope that this would induce cylindrical initiation.

The first two possibilities were not considered to be acceptable. In the first case, if the force of the detonation in the core were sufficient to cause expansion of the tapered steel element and breakup of the explosives, it would probably be sufficient to break an outer case as well. Figure 6 shows a frame from a charge prepared with ¼-in. steel confinement surrounding the explosive. Note that the metal has been expanded and severely cracked around the base of the charge, and yet no detonation products are visible. Along the end of the charge, however, a cracking can be seen, with detonation products punching through the case.

The second possibility was not considered to be satisfactory, since movement of the base portions of the core would require a large diameter charge to prevent compression of the tetryl beyond the limits of the encasing material. Such large diameter charges would not be practical for application in the Terrier, or for that matter in any other warhead.

The third possibility has many of the disadvantages of the second, since the size of the required cavity would be excessive for application to Terrier. At the measured velocities of the material of the core, both at the base and at the terminal end, a five-inch-diameter cavity would be required. Such a method, however, furnished a better solution since there would be no problem of explosive breakup.

The final solution actually involved both the second and third possible solutions as well as a repetition of the basic concept of wave

shaping. Figure 7a shows a working device which was developed to fire from the center since a satisfactory 8-in.-long initiator could be produced. The 16-in. and the 8-in. device have yielded excellent results when used in firing experimental warheads or smaller units for testing warhead elements. Figure 8 shows open-shutter photographs of the firing of these warheads using this 16-in. initiator. Jets from the conical elements can be seen striking the target surfaces, showing the effect of the initiator.

Further studies are being conducted at this laboratory to develop an initiator on this basis which will be end-detonated, and which will fire directly into cast explosive instead of the low-density tetryl now in use. In this manner, a device can be had which is adaptable to safety requirements for guided missile applications.

The cylindrical initiator functions on the principle of a delay element type of wave shaping device. A lateral wave is created by the expansion of the central steel element under the influence of the products of detonation of the contained explosive (see Fig 5). This detonation wave is not uniform along its entire length, but, because of the variation in thickness of the steel core, there is a gradient in velocity and temperature of the gases comprising the wave. However, the direction of motion is essentially perpendicular to the axis of the charge. The effect of the outer tapered sleeve, then, is to impose upon this wave a variable delay such that sufficient energy is passed on to the other explosive, probably by a shock through the element, to cause initiation which is essentially simultaneous over the entire length, the actual mechanism of the initiation being that described by Cook in this symposium.

The effect of expansion should also be mentioned again in relation to breakup of the explosive surrounding the sleeve. Any delay or shaping of the wave must be accomplished before the explosive can be damaged to the extent that initiation is not likely. It would appear that some strong material, such as steel, brass, or copper would be much more effective in such an application because of their greater tensile strength. However, such does not appear to be the case. During the course of the investigation of wave shaping at the University of Utah (Ref 4), it was found that an aluminum element had only sufficient delay to create a plane wave, whereas almost complete interruption could be obtained with the same size and shape constructed from steel. Thus, delays through steel are very

much greater than through aluminum. This larger delay permits the material expanding from the core to bear for a sufficient length of time to cause breakup of the steel and severe damage to the explosive.

This particular device promises to be of considerable value both as an initiator in ordnance applications and as a tool for experimental purposes. With certain modifications, as outlined previously in this paper, a practical service initiator can be produced for use in applications where it is desired to project particles or jets in a direction perpendicular to the axis of the projectile. This would mean that the pattern of a fragmentation-type warhead would be more concentrated than is probable with conventional means of initiation. For a rod warhead it would make the utilization of explosive energy more efficient than is possible with the use of inert padding. For a shaped-charge warhead it would make possible the efficient collapse of all cones in the warhead with a symmetrical wave. This would increase both the probability of a hit and an effective kill on the aircraft, leading to an effective weapon for defense against air power.

REFERENCES

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2 R. H. Stresau, and J. Savitt, *Detonation for Multiple Point Simultaneous Initiation of Explosive Charges*, NAVORD Report 2114 (CONFIDENTIAL)

3 Technical Report No. XXXI, Contract No. N7-onr-45197, Project No. 357-239, Explosives Research Group, March 15, 1954 (CONFIDENTIAL)

4 Technical Report No. XXXVIII, Contract No. N7-onr-45107, Project No. 357-239, Explosives Research Group, September 20, 1954

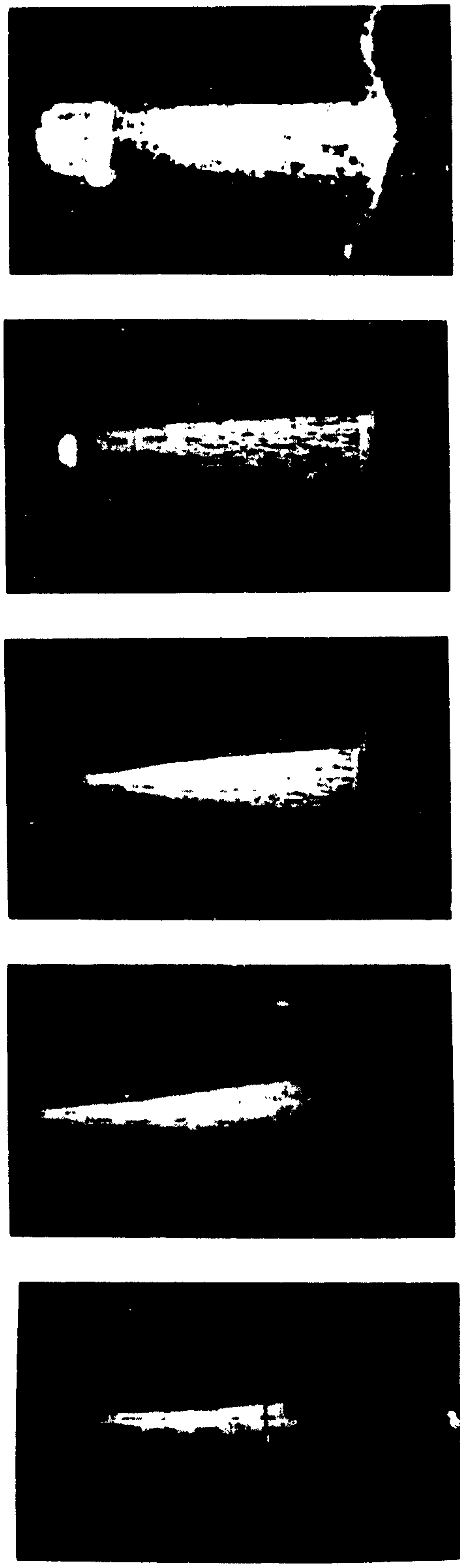
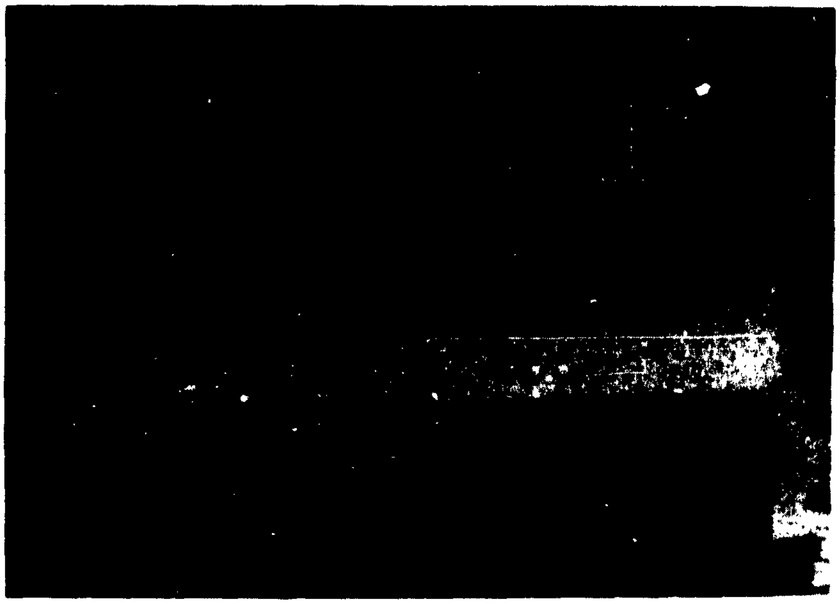
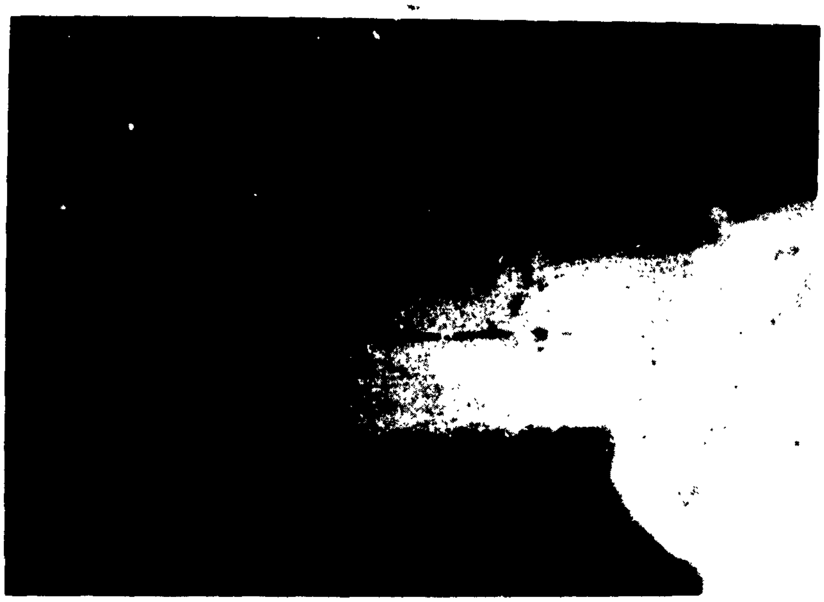


Fig 5 Rotating-Mirror Framing Camera Photograph of Expanding Steel Core (3 μsec between pictures)



a. Static Image of Charge Prepared for Firing



b. Approximately 50 μsec after Detonation of Cap

Fig 6 Effect of ¼-Inch Steel Confinement on Charge of Figure 4

PARTS LIST

Part	Req'd	DESCRIPTION
①	2	END PLATE - ALUMINUM
②	1	CORE-STEEL (.015) x Max. Wall .407" Min Wall .032" .625" ID 1.439" OD (End Center) Tapered from Center. Taper Length 8.0". Overall Length 18.50". Drill Tap to Accomodate ⑤
③	1	SLEEVE - ALUMINUM 61 ST Max. Wall .075" Min. Wall .049" 2.0" ID, 2.150" OD (Center), 2.375" OD (End) Tapered from Center. Taper Length 8.0" Overall Length 18.50".
④	1	PLUG-STEEL DRILL ROD. ¼-20NF Recess .125" x .285" ID. Drill to Accomodate Insulated Cap Wires Max Length of Plug .375"
⑤	1	DETONATOR M36, With Extension Leads Attached.
⑥	1	PLUG - LEAD .098" Thick, One Side Curved To Fit Wall Of ②.
⑦	1	OUTER SLEEVE - ALUMINUM 3" ID Max. Wall .032".

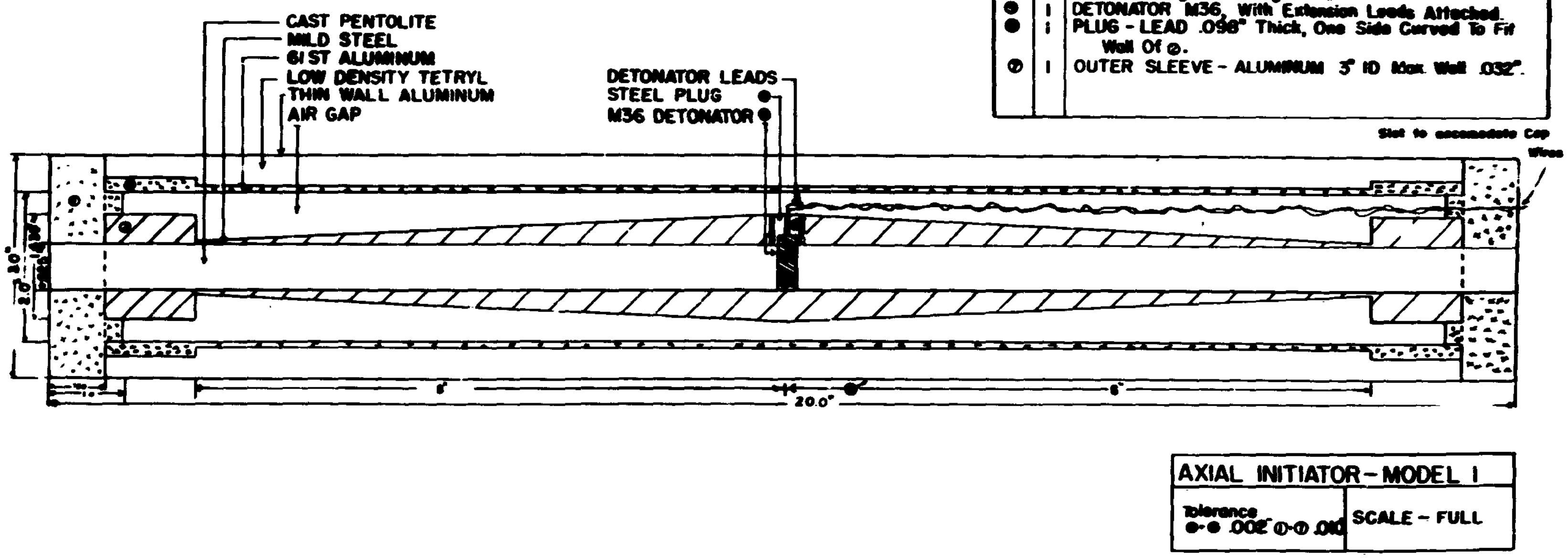


Fig 7a Sixteen-Inch Cylindrical Initiator

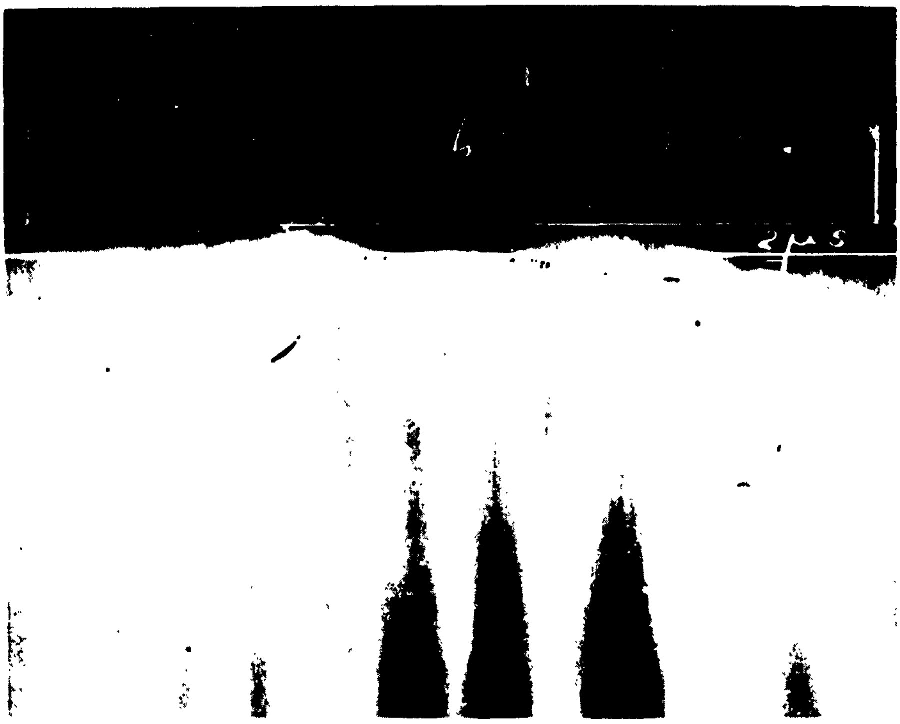


Fig 7b Rotating-Mirror Streak Camera Trace of Wave from Sixteen-Inch Initiator

a. Steel Cones (left) and Zinc Alloy Cones (right)

b. Aluminum Cones

Fig 8 Firing of Multiple-Shaped Charge Warheads Using Sixteen-Inch Cylindrical Initiator

EFFECTS OF ASYMMETRY ON SHAPED DETONATION WAVES

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Carnegie Institute of Technology

INTRODUCTION

The purpose of this paper is to emphasize a shortcoming of wave-shaping techniques which is important enough to be of grave concern to investigators who are attempting to apply these techniques to practical situations. This shortcoming is the tendency to magnify very seriously small random asymmetries, which, under ordinary point initiation, could be tolerated. The resulting adverse effect is particularly noticeable in the case of shaped charges. The establishment of a good jet upon collapse of a shaped charge liner depends critically on the exact cancellation of radial momentum at the liner axis, and the entire collapse process must be symmetrical to a high degree about this axis. Consequently, the detonation front in contact with the liner at any instant must also possess this axial symmetry. To obtain a given degree of symmetry, much tighter tolerances are required in cases where wave-shaping methods have been employed than in the case of point initiation.

It is reasonable to expact that any other application of wave shaping techniques which relies heavily on symmetry will be similarly affected by small misalignment. Thus great care must be exercised, in practice, if the expected benefits of wave shaping are to be realized in such cases. Indeed, from the point of view of practical weapons development, the production problems are so aggravated that the theoretical benefits of the shaped wave should be thoroughly understood and evaluated before one embarks on such a course. Here again, the shaped charge field offers a good example. Since as early as the second World War, attempts have been made now and again to produce conically shaped waves for shaped charges, on the erroneous assumption that normal incidence of the wave on the liner was the optimum condition. The fact that peripheral initiation improves shaped charge performance at all is due chiefly to the fact that it produces a more nearly optimum rate of progress of the wave front along the liner wall. The optimum rate is by no means infinite, which would be the value obtained in the case of normal incidence.

The point of view expressed in the foregoing, regarding asymmetries

in shaped waves, is based largely on three factors: first, the result of penetration studies of a peripherally initiated shaped charge; second, geometrical considerations based on spherical expansion; and third, streak camera records of asymmetries in wave fronts from peripheral initiators.

PENETRATION EXPERIMENTS

The penetration studies were made on a charge designed by the Naval Ordnance Laboratory (Fig 1). The charge contains an M9A1 steel cone, and a barrier of lead oxide. The explosive is pentolite. The main charge was cast over the cone and machined to the desired height. The cap was cast separately, filled with lead oxide, and centered on the main charge.

Initial tests at NOL[1] indicated that there existed an optimum charge length which gave a maximum improvement in penetration of 46% over a point-initiated charge of the same length at a 4-inch standoff. Their results are shown in Figure 2, which is a figure from their report comparing peripheral initiation with point initiation and plane wave initiation. Figure 3 shows the individual shots for the peripheral case. The scatter is very large in the shorter charge lengths. This is to be expected, as will be seen.

This experiment was repeated by the group at CIT with the same charge design and nominally the same liner. The result was an improvement of only 20%. Again the variability in the penetrations was large. With the cooperation of NOL, a series of penetration experiments was performed in an effort to isolate the source of the discrepancy. Charges and liners obtained from NOL were combined in various ways with those used at CIT. The results are shown in Figure 4. It is apparent from these plots that the liner was the component that caused the major portion of the discrepancy. To increase the statistical significance of this result, some fifty odd shots were made for each group. The results, plotted in Figure 5, show clearly the superiority of the NOL liners (Lot A) over the CIT liners (Lot B) under peripheral initiation. This conclusion was substantiated in private communication with the NOL group regarding a series of tests with the CIT cone.

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[1] B. E. Drimmer and W. T. August, *Peripherally Initiated Shaped Charges*, NAVORD 1722 (NOL 9863), Naval Ordnance Laboratory, November 1, 1950

An attempt was made to find differences in the two groups of liners that could account for the large difference in performance with peripheral initiation. The CIT liners were manufactured by the United Specialties Company while the NOL liners were probably supplied by the Budd Company. The only difference distinguishable by present gaging methods was an 8% difference in wall thickness, the CIT liner being thinner than the NOL liner. Measurements of contours, heights, and angles showed no significant difference, and density measurements differed by less than 2½%. Jet velocity, penetration time, and hole volume measurements failed to show any trends that could be traced to physical differences between the two cones. Most significant of all, for our purpose here, is the fact that the penetration performance of the two lots under point initiation was essentially identical.

This is not the first time that such peculiarities have cropped up in the study of charges which involve wave shaping techniques. The use of slow core binary charges to produce an inverted wave somewhat similar to the peripheral case is well known. We quote from OSRD 3443, dated April 1944:

> "On obtaining a new lot of Budd cones, the improvement with the core was again observed. It is difficult to imagine what subtle difference could exist between this set of United Specialty cones and the Budd cones, which would appear solely in response to the effect of the TNT core, without being reflected in the normal performance in an all pentolite charge."

It is now felt that undetected distortions in the United Specialty cones led to small asymmetries in the assembled charge which were sufficient, under peripheral initiation, to cause the lower penetrations.

The variability in the performance of standard point initiated charges has made their investigation difficult in the past, and will continue to do so until they can be made more reproducible. This factor is even more troublesome in the case of peripherally initiated charges. The large variability evidenced by this type of charge is due to its extreme sensitivity to asymmetries in alignment compared to that of the point-initiated charge. Any slight imperfection in the explosive, or in the alignment of the cone or the initiator will cause unsymmetrical collapse of the liner and will

have greater deleterious effect on the jet. The potential advantage of peripheral initiation is easily lost by imperfect construction.

GEOMETRICAL CONSIDERATIONS

The sensitivity of the peripherally initiated shaped charge to asymmetries can be understood in terms of the geometry involved. Consider a charge of homogeneous explosive whose boundaries are far enough removed from the liner that they play no part; i.e., as sources of rarefaction waves. Assume, further, that the cone is perfect and thus has a well-defined axis. In such a case the geometry of point initiation, as far as symmetry is concerned, is specified solely by this axis and the point of initiation, and the only asymmetry involved is the displacement of the point of initiation from the axis. (We assume that the plane of asymmetry has been specified.) The geometry of peripheral initiation, on the other hand, involves several independent parameters. If we assume a perfect cylindrical barrier as well as a perfect liner, the configuration is specified, as far as symmetry is concerned, by two axes and the point of initiation. Asymmetries can include misalignment of the barrier relative to the liner, and misalignment of the point of initiation relative to the barrier. A convenient way to describe these asymmetries is shown in Figure 6. The angle θ between the two axes, and the displacement r of the midpoint of the barrier face from the cone axis determine the former misalignment; the displacement δ of the point of initiation from the barrier axis determines the latter. Of course these three asymmetries, θ, r, and δ, need not all take place in the same plane. The various difficulties will not necessarily add up, but on the other hand can never entirely cancel each other because of their different natures. Let us consider them individually.

It is first necessary to define the "tilt" of the wave. In both cases, the intersection of the wave front with the liner at any instant defines a plane. The angle ϵ between the normal to this plane and the cone axis is taken as a measure of the tilt. The angle ϵ can be determined as a function of the axial position x of the detonation front relative to the liner apex, for given charge geometry and asymmetries. Representative curves have been plotted for each of the asymmetries described, on the basis of the charge geometry used in the penetration experiments. The details given in the appendix will facilitate similar calculations for other geometries.

The case where r is the only asymmetry involved is shown in Figure 7.

It is seen that for an eccentricity of 0.01 inch the tilt is at least two or three times greater for peripheral than for point initiation, over the upper half of the liner, and is many times greater near the apex. On the other hand, a full 0.1-inch eccentricity in the point case yields values which are of the same order of magnitude as those of the 0.01-inch peripheral case near the apex of the liner. When δ is the only asymmetry involved, the result is even more serious. Figure 8 compares the case for $\delta = 0.01$ inch with point initiation eccentricities of 0.01 inch and 0.10 inch. A 0.5 degree asymmetry in θ is shown in Figure 9. The results are similar to the case of $r = 0.01$ inch.

The presence of these three asymmetries in various random combinations can be expected to have a much more serious effect on shaped charge performance than will misalignment of the same order of magnitude in the case of point initiation.

In addition to the fact that more independent asymmetries are possible in the peripheral case, it should be remembered that the practical application of this technique generally involves much shorter charges than the equivalent point-initiated case. To the extent that inhomogeneities in the explosive can be ignored, asymmetries in initiation are ironed out as the wave proceeds down the charge. Thus the shorter charges used in these applications can be expected to show increased variability.

STREAK CAMERA RECORDS

The wave shape asymmetries discussed above can be easily detected, and measured with a fair degree of accuracy, by means of the rotating-mirror camera at CIT. This is a "homemade" camera which is ideally suited to this purpose because of its large magnification and high writing speed. Magnification of the order of 1.3 and writing speeds approaching 1 cm μ sec are available.

An example of the type of record obtained with this camera is shown in Figure 10. The record is that of a 1-inch long, point-initiated charge of Composition B. Such traces agree sufficiently well with predictions based on spherical expansion to justify the use of the assumption for our purpose here.

Figure 11 shows the case of peripheral initiation. The wave is made

to pass around a cylindrical barrier of inert material and expands spherically from the circular edge. The streak record has been constructed for three different charge lengths. The actual records for such charges are shown in Figure 12. These traces show the development of a Mach bridge in the acute angle formed by the intersection of the parts of the wave. The Huygens' construction does not, of course, account for this bridge, but otherwise the agreement is quite good.

If the detonator is displaced ¼ inch off center the construction is as shown in Figure 13. In Figure 14 we compare, at the same charge length, three different situations regarding symmetry. The trace on the right shows no measurable asymmetry; the trace in the center shows a large difference in arrival times for the two branches, corresponding to a large δ asymmetry, with negligible r asymmetry; and the left hand trace shows large r asymmetry with very little δ asymmetry. These three charges are all nominally symmetric. These are the asymmetries which just happened to show up along the diameter defined by the camera slit.

SUMMARY

It is concluded, on the basis of the above experimental results and geometrical considerations, that the application of peripheral initiation to shaped charges greatly increases the sensitivity of such charges to slight misalignment of the components. For this reason no serious consideration has been given to incorporating wave-shaping techniques in HEAT weapons with the ultimate aim of increasing the penetration. It is reasonable to expect similar difficulties with wave-shaping techniques in other applications which require a large degree of symmetry.

APPENDIX

The tilt is given by

$$\tan \epsilon = \frac{x - x'}{x + x'} \; \frac{1}{\tan \alpha}$$

where x' is shown in Figure 15. x' can be found as a function of x for each asymmetry as indicated below.

<u>r asymmetry:</u> From Figure 15 (a) we have

$$(R - r - \tau)^2 + (h + x)^2 = U^2t^2$$

$$(R - r' + \tau)^2 + (h + x')^2 = U^2t^2$$

where U is the detonation rate, and t is the time measured from the arrival of the front at A and A'.

δ asymmetry: From Figure 15 (b) we have

$$(R - r)^2 + (h + x)^2 = U^2t^2$$

$$(R - r')^2 + (h + x')^2 = U^2t'^2$$

where $t - t' = 2\delta/U$ since 2δ is the path difference from the point of initiation to A and A'.

θ asymmetry: From Figure 15 (c) we have

$$(R \cos \theta - r)^2 + (h - R \sin \theta + x)^2 = U^2t^2$$

$$(R \cos \theta - r')^2 + (h + R \sin \theta + x')^2 = U^2t^2$$

In each case, we can eliminate the time, set $r = x \tan a$, $r' = x' \tan a$, and solve for x' as a function of x. The results are listed in the accompanying table. For a given geometry, the sign before the radical in each case is chosen so that $x' = x$ when the asymmetry is zero.

The dimensions used for the calculations plotted in Figures 7, 8, and 9 are h = 0.3 inch, R = 0.75 inch, a = 22 degrees. The calculations are applicable to any case where R/h = 2.5 and a = 22 degrees if the asymmetries and the values of x are scaled accordingly.

$$r\colon\ x' = \cos^2 \alpha \left\{ (R + r) \tan \alpha - h \pm \sqrt{[(R + r) \tan \alpha - h - x \sec^2 \alpha]^2 - 4 \sec^2 \alpha\, r\, (R - x \tan \alpha)} \right\}$$

$$\delta\colon\ x' = \cos^2 \alpha \left\{ R \tan \alpha - h \pm \sqrt{[R \tan \alpha - h - x \sec^2 \alpha]^2 - 4 \sec^2 \alpha \left(\delta \sqrt{(R - x \tan \alpha)^2 + (h + x)^2 - \delta^2}\right)} \right\}$$

$$\theta\colon\ x' = \cos^2 \alpha \left\{ R (\cos \theta \tan \alpha - \sin \theta) - h \pm \sqrt{[R (\cos \theta \tan \alpha - \sin \theta) - h - x \sec^2 \alpha]^2 - 4 \sec^2 \alpha\, R \sin \theta\, (h + x)} \right\}$$

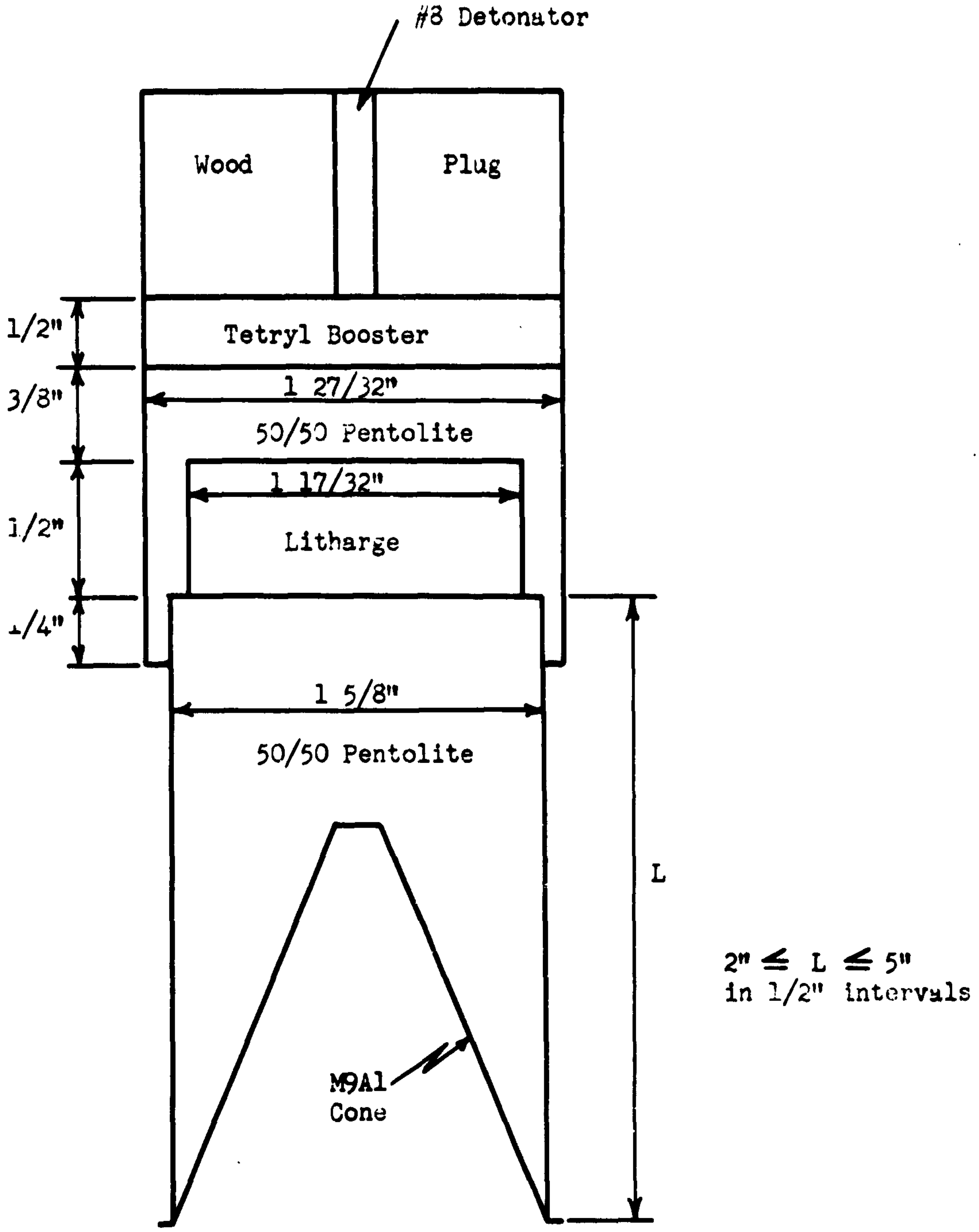

Fig 1 Peripherally Initiated Charge Design Used at the Naval Ordnance Laboratory.

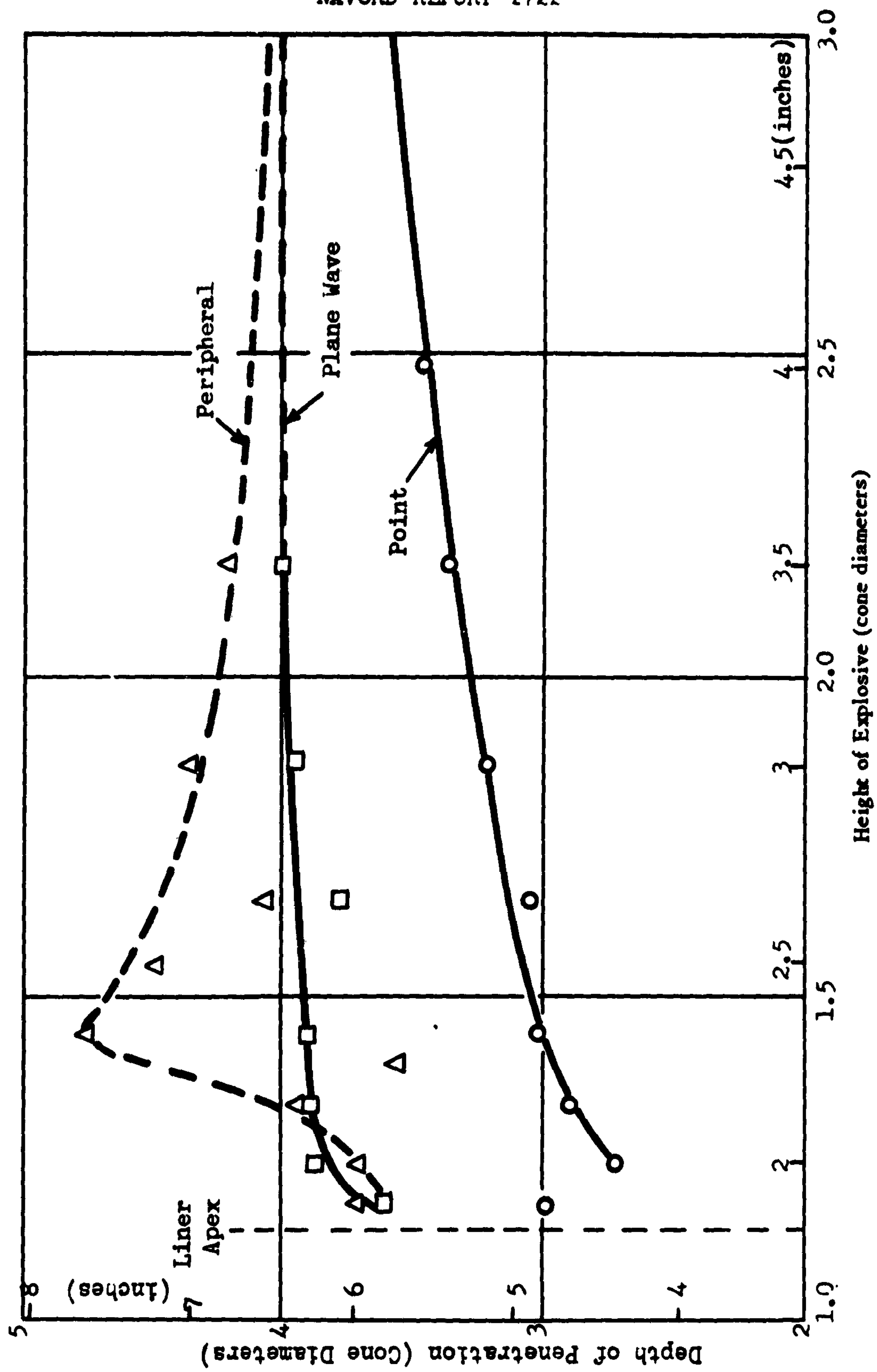

Fig 2 Depth of Penetration With Different Initiating Systems.

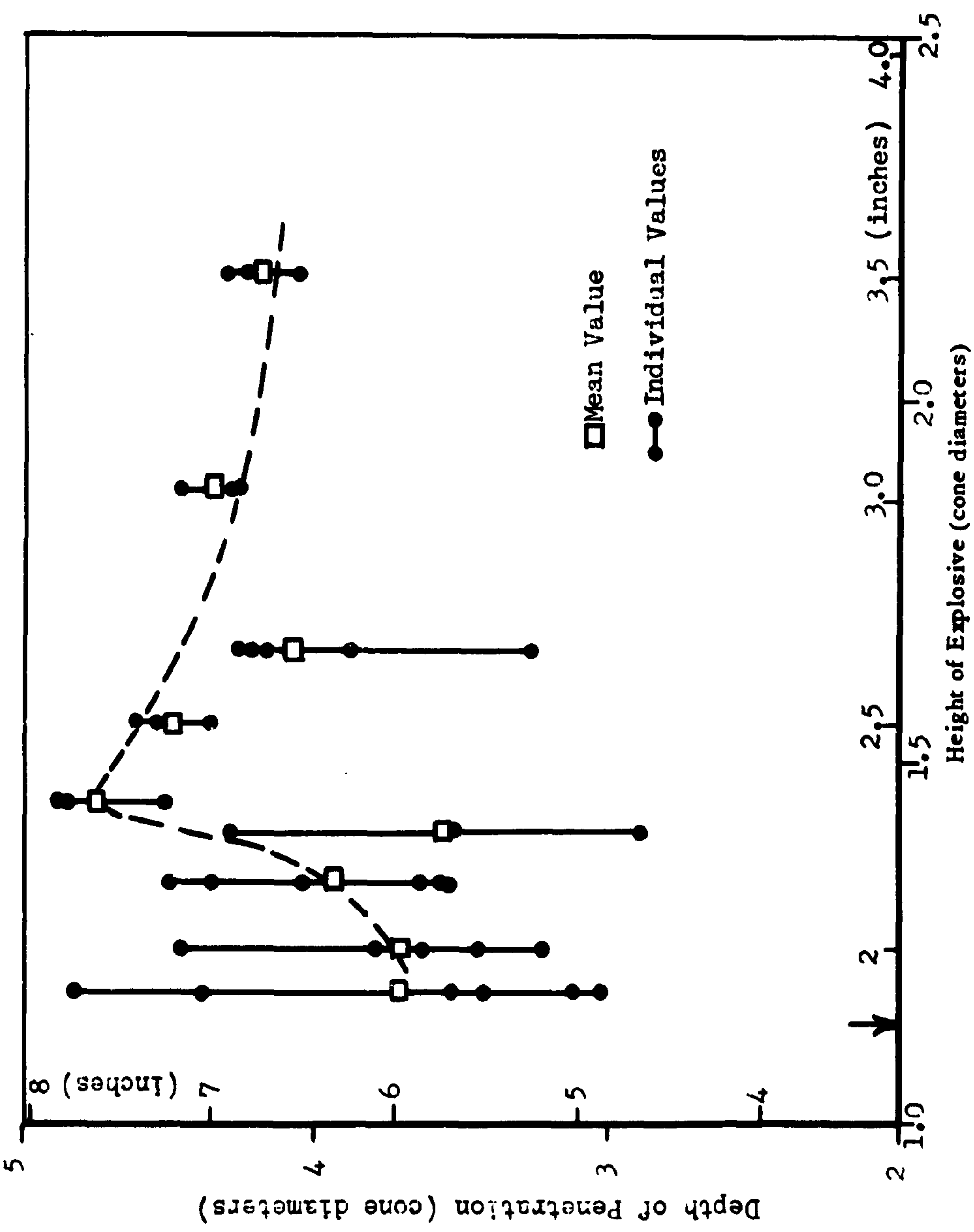

Fig 3 Depth of Penetration With Peripheral Initiation.

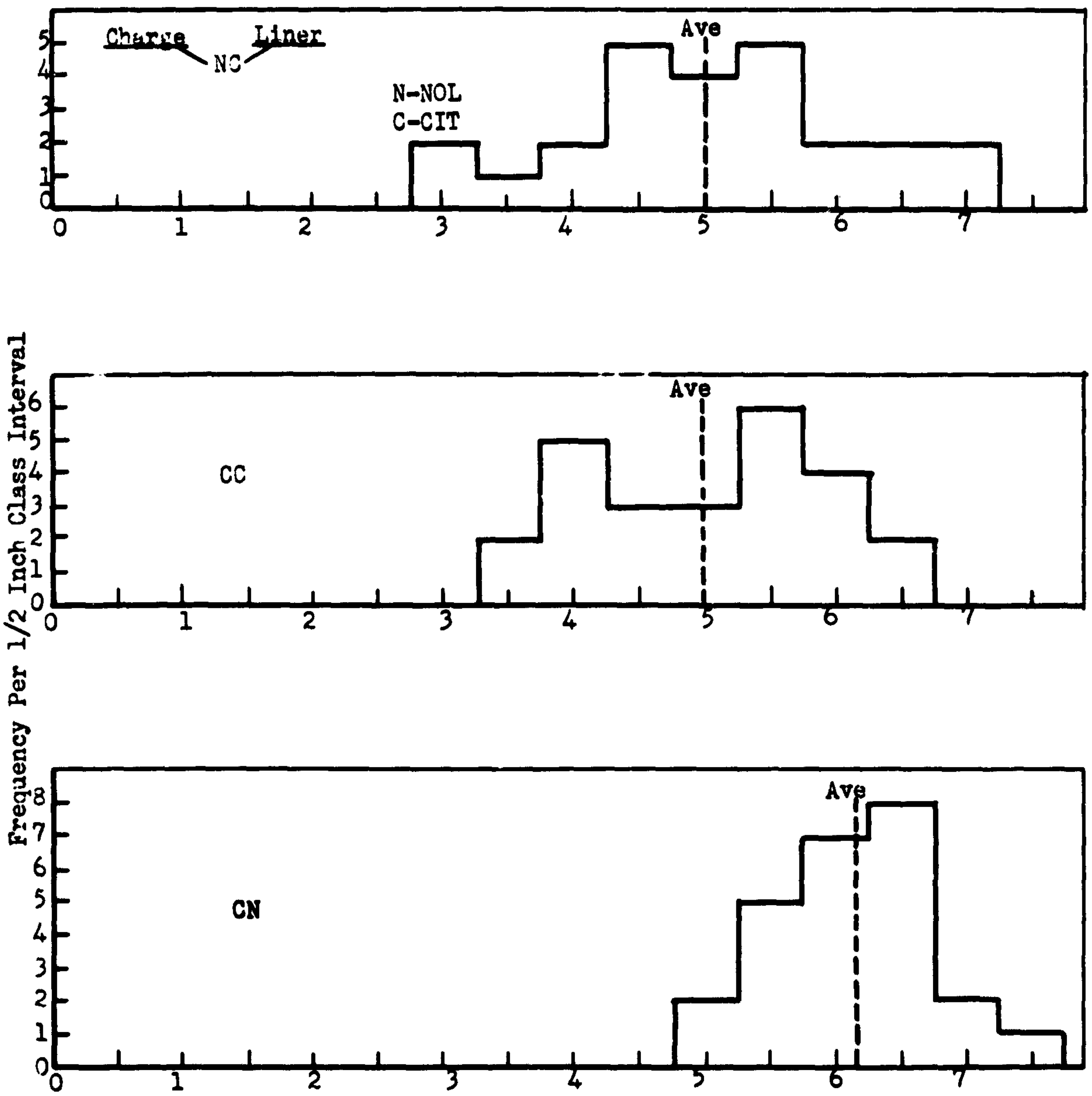

Fig 4 Penetration Histograms for Various Combinations of NOL and CIT Charges and Liners (Peripherally Initiated).

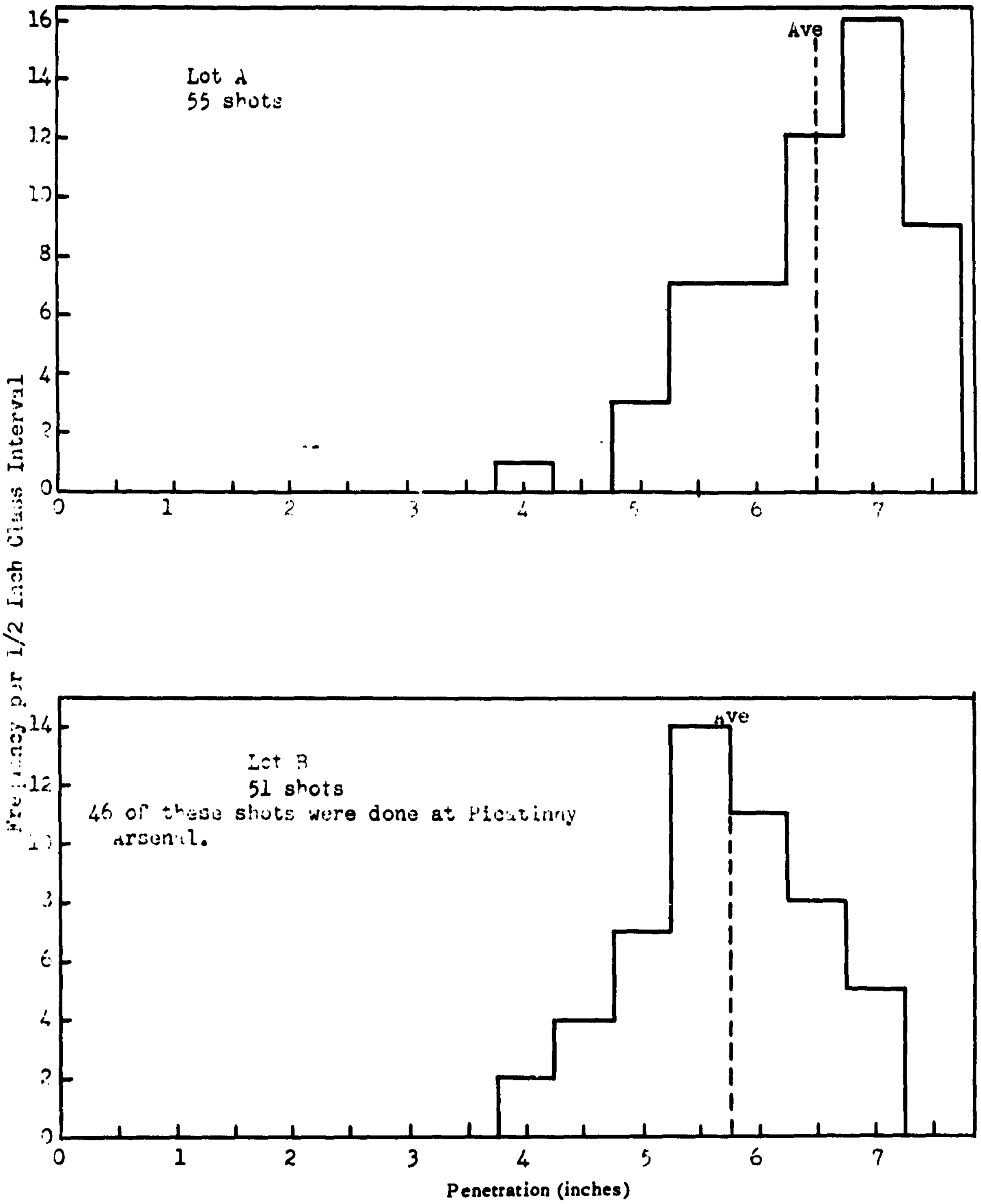

Fig 5 Penetration Histograms for Comparison of Lot A & Lot B Liners in Peripherally Initiated Charges.

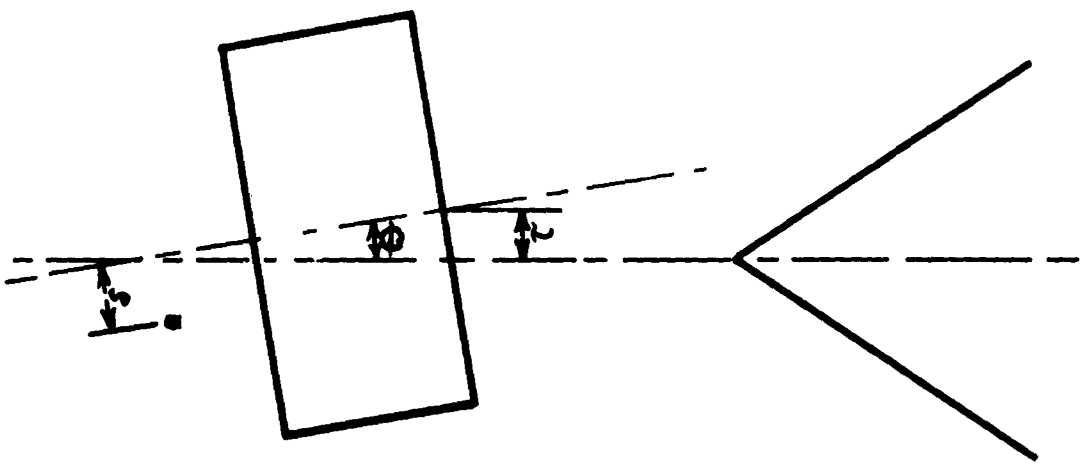

Fig. 6 Asymmetries involved in peripheral initiation.

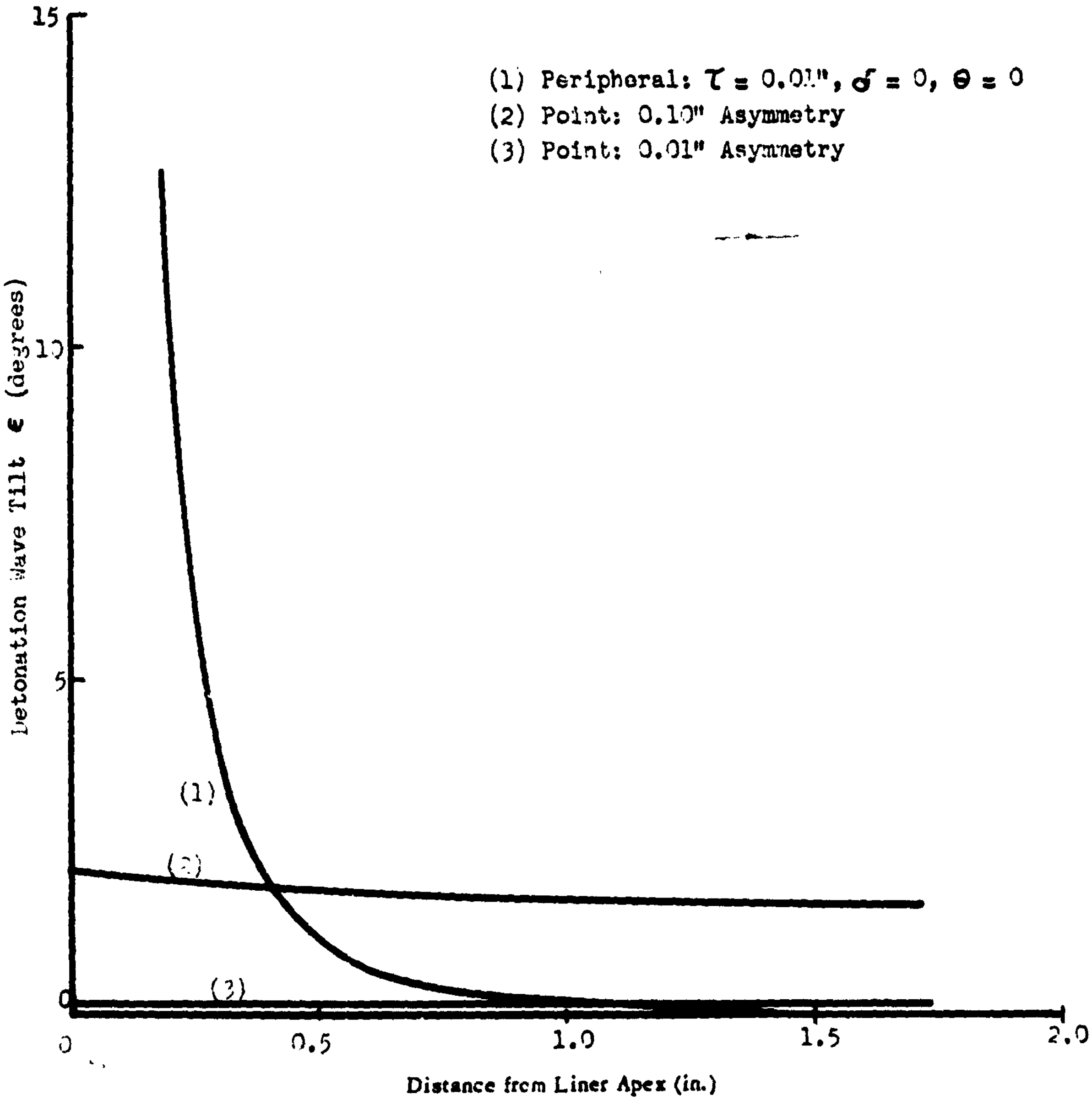

Fig 7 Detonation Wave Tilt Due to r Asymmetry.

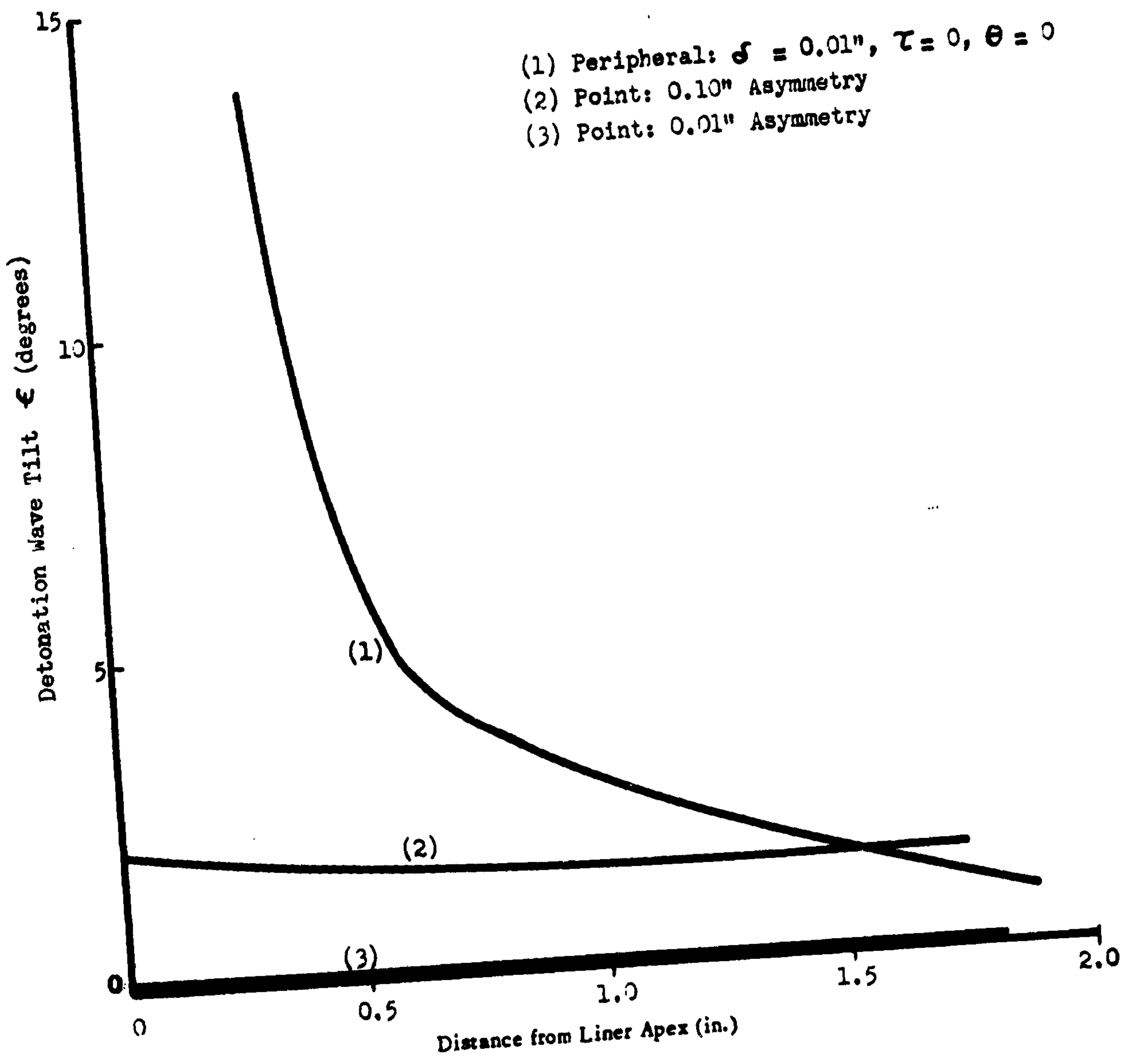

Fig 8 Detonation Wave Tilt Due to δ Asymmetry.

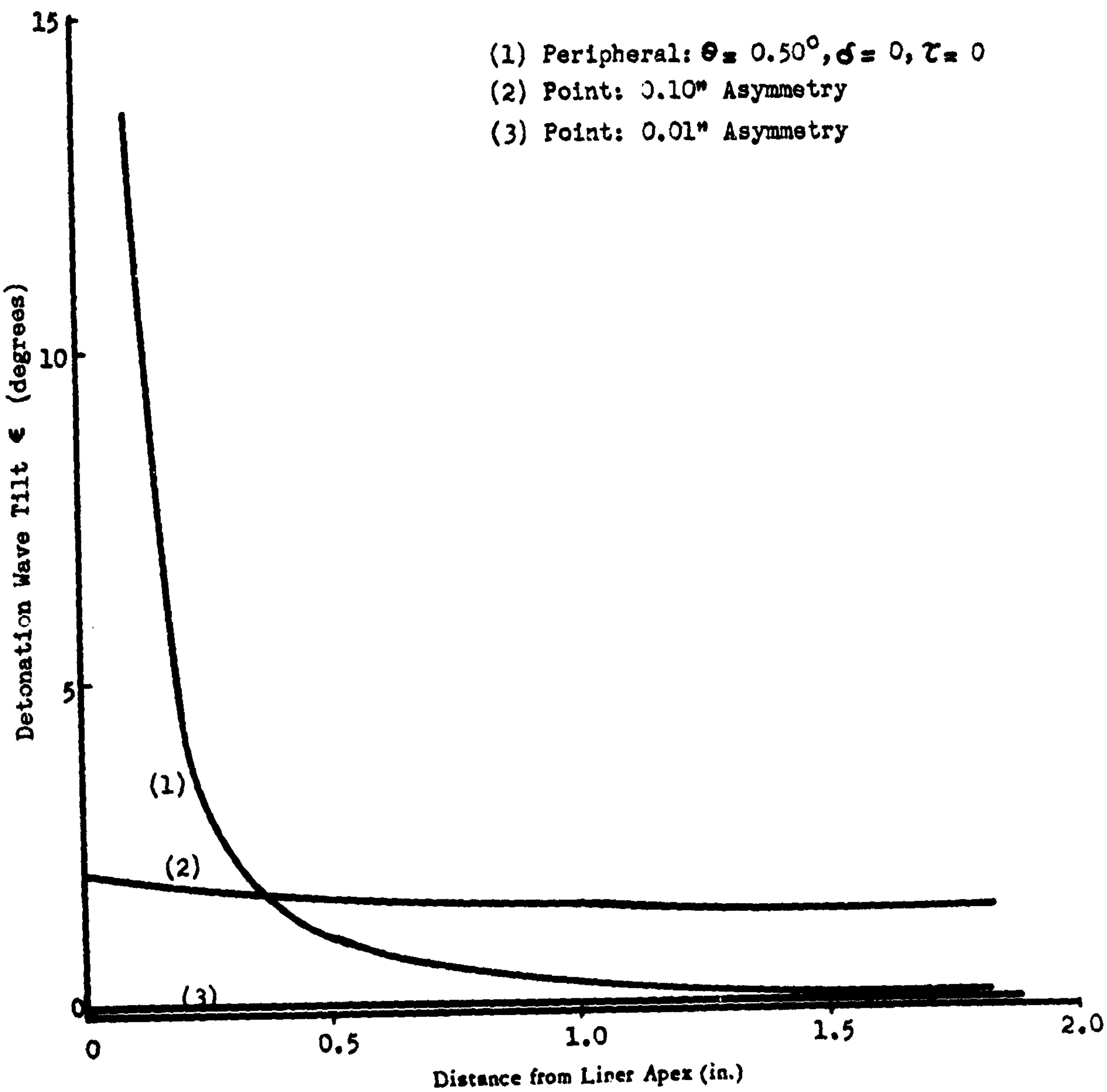

Fig 9 Detonation Wave Tilt Due to θ Asymmetry.

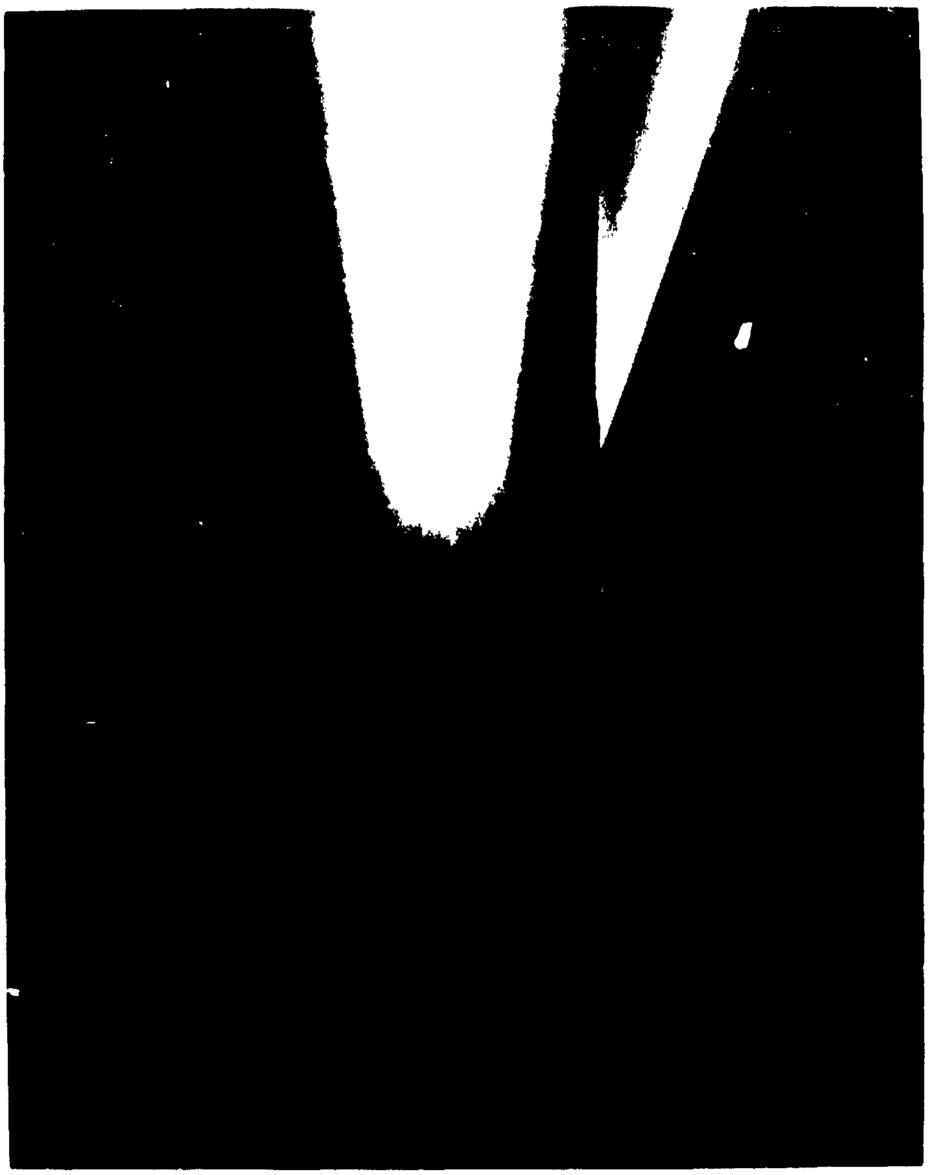

Fig 10 Streak Camera Record of Point Initiation

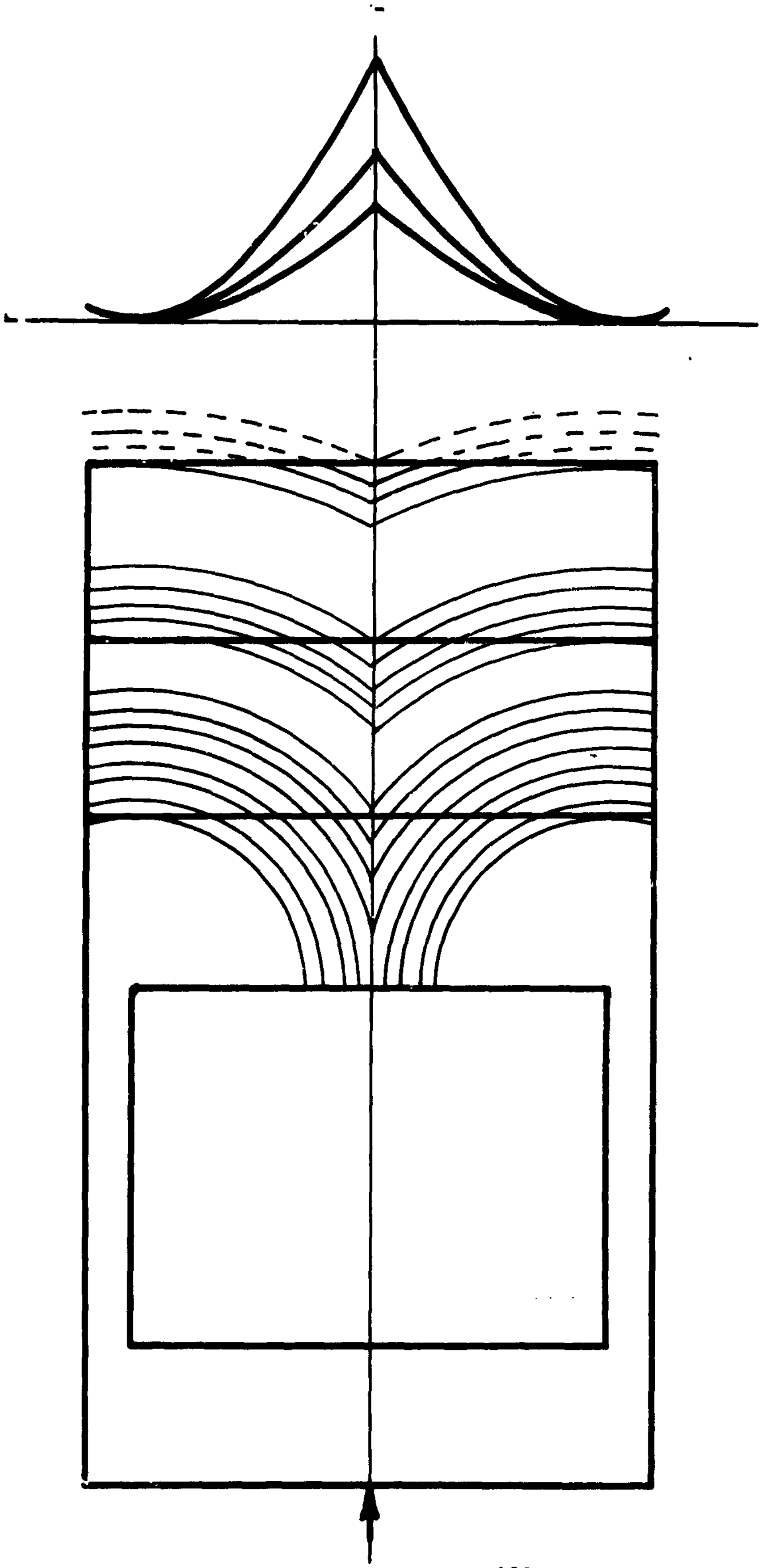

Fig. 11. Construction of streak camera record for peripherally initiated wave at three charge lengths: $\frac{L}{D} = 0.31, 0.62, 0.93$

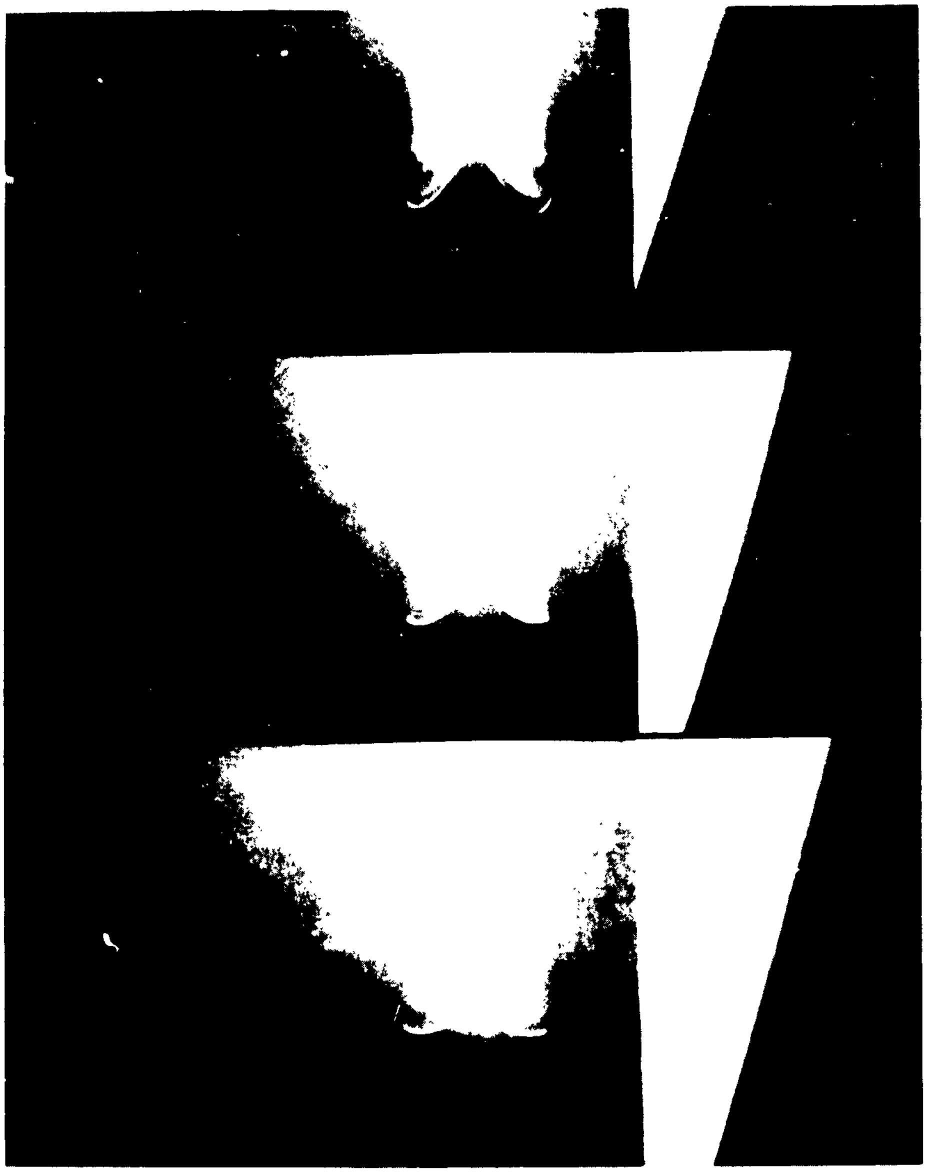

Fig 12 Streak Camera Record of Peripheral Initiation

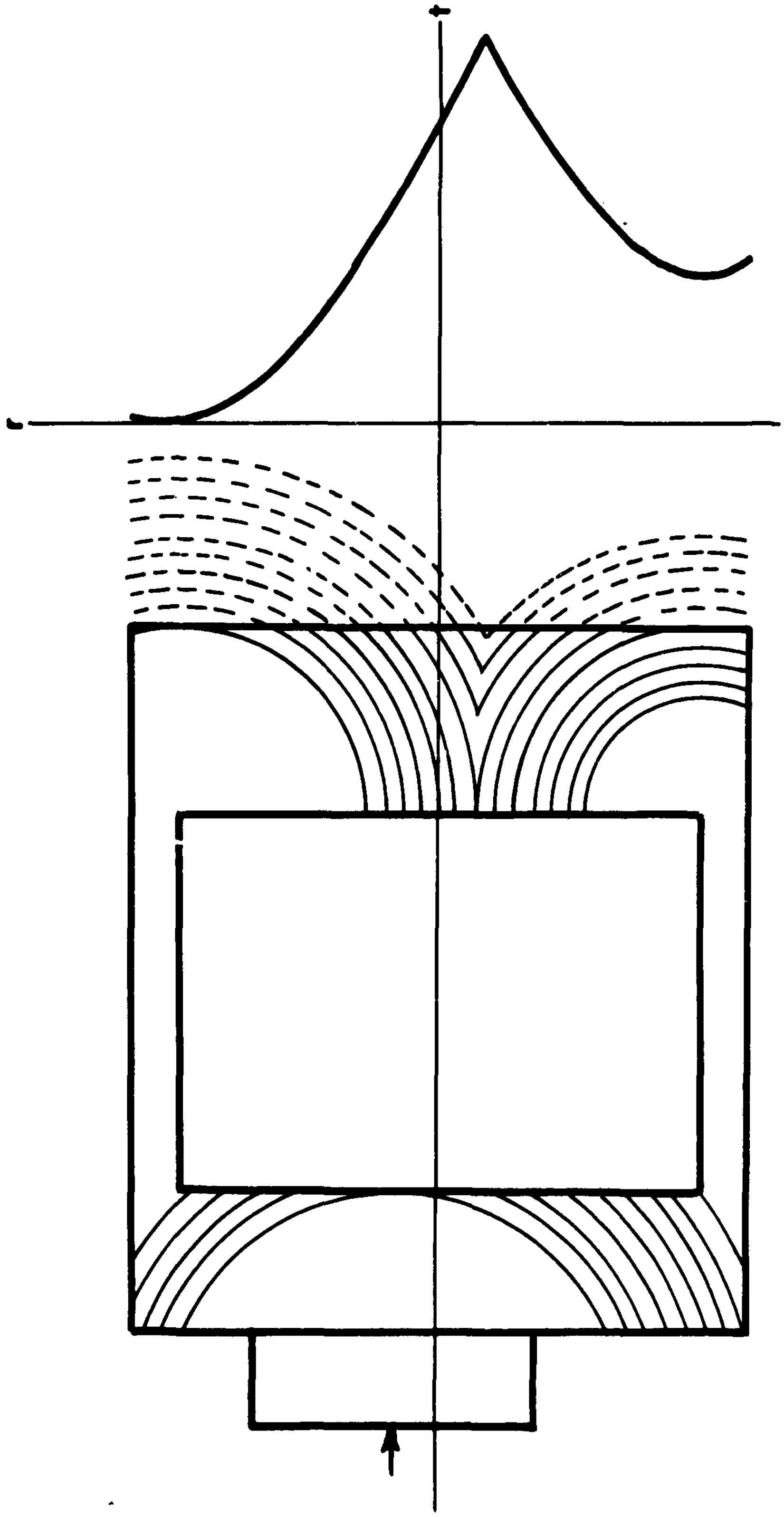

Fig. 13 Construction of streak camera record for asymmetric peripherally initiated wave.

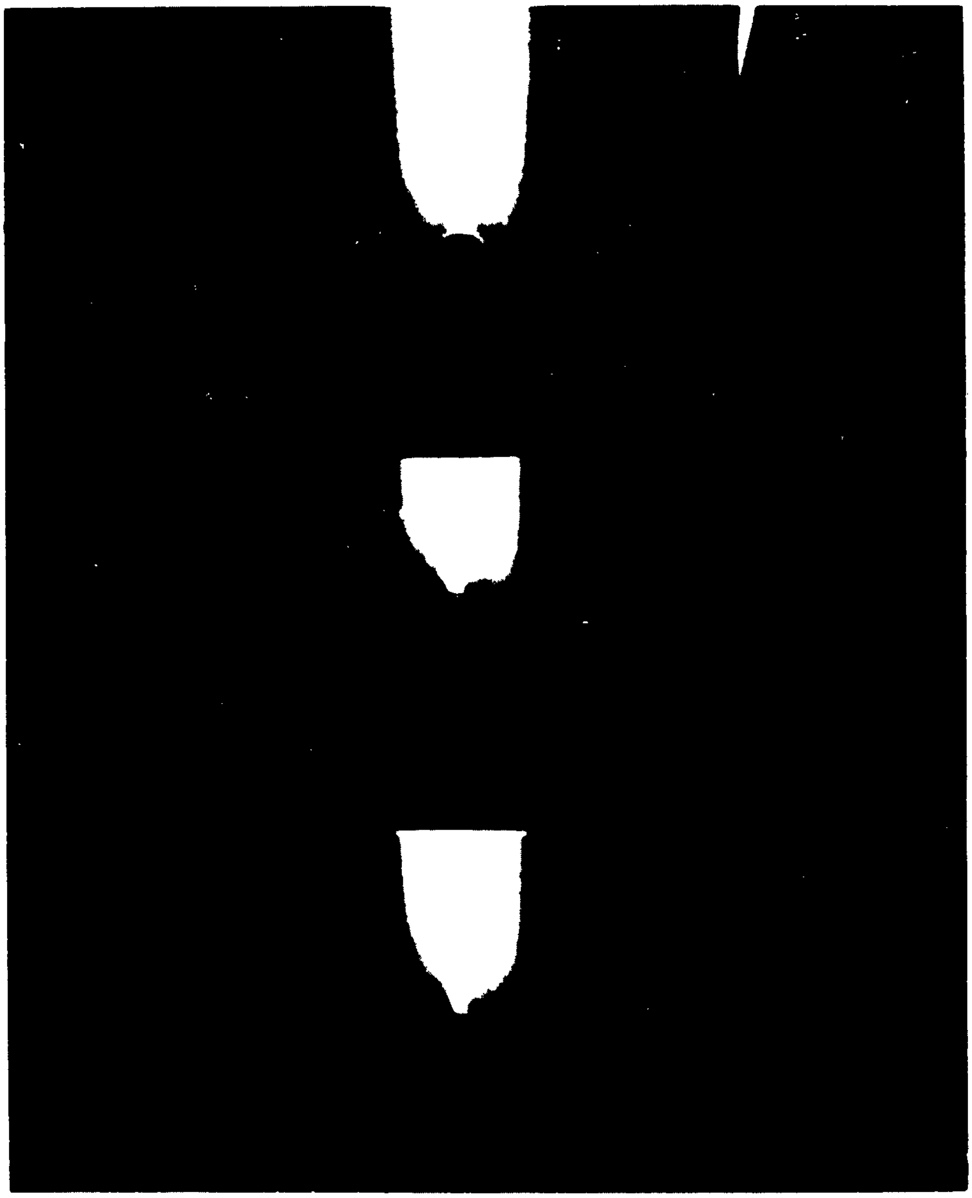

Fig 14 Comparison of Asymmetries in Peripherally Initiated Wave Fronts

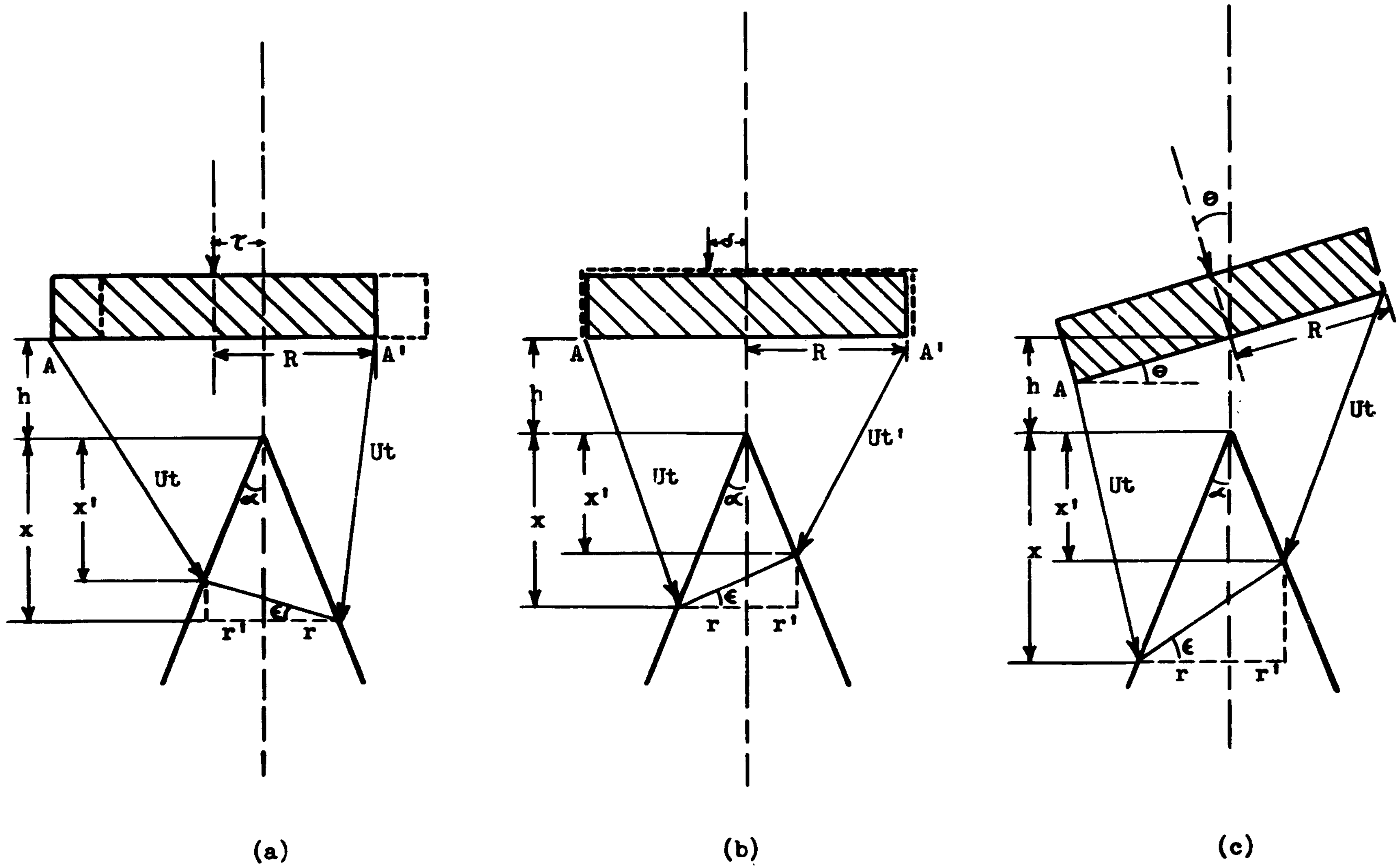

Fig. 15 Construction of detonation wave tilt for asymmetries in peripheral initiation.

STUDIES ON THE NOL PLANE WAVE BOOSTER

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ABSTRACT

The NOL type plane wave booster reported in NAVORD Report 3620 is described. The results of recent studies to gain better understanding of the design variables are presented.

INTRODUCTION

The NOL plane wave booster, in its simplest form, is composed of a detonator; a flat explosive slab, called the donor; a flat metal plate, called the transfer plate; and another explosive slab, called the acceptor, which has a shallow cavity facing the detonator (see Fig 1). The diverging wave from the point of initiation is re-shaped to a plane wave by the delaying action of the relatively low velocity of the transfer plate across the cavity. The prototype booster is fully described in NAVORD Report 3620. Since the writing of this report, studies have been made of the effects of varying design factors, such as the thickness of the donor or transfer plate. This paper is concerned with the highlights of the overall work on the booster.

INITIAL DESIGN CONSIDERATIONS

In designing a general-purpose booster the best ratio of the detonation velocity in the donor to the transfer plate free surface velocity seems to be between 7:1 and 10:1, although it may be possible to go as high as 12:1. Most readily available high explosives, such as pentolite, Composition B, or 75/25 cyclotol will have a detonation velocity in the range of 7500 to 8200 m/s. However, the transfer plate velocity should be in the range of 900 to 1200 m/s. If it is much lower than 900 m/s, the acceptor may not reliably initiate. If it is much higher than 1200 m/s, the cavity must be quite deep. The transfer plate material must be dense enough to enable reasonably thin plates to be used, i.e., 1/8 to 1/4 in. thick. The material must be strong enough to be machined or ground to precision flatness over diameters that are large relative to the thickness. Transfer plates of brass, copper, and mild steel have been tested, with

steel requiring the least complicated cavity profile.

The acceptor explosive can be made of explosives having a wide range of sensitivities. Tests made with 4-in.-diameter, 1-in.-thick pentolite donors and 0.180-in.-thick steel transfer plates indicate that cast acceptors of 50/50 pentolite, 75/25 cyclotol, Composition B, and HBX-1 can be used with about equal results. The greatest noticeable difference is near the edge of the cavity. Pentolite has the largest useful diameter, i.e., it is plane over a slightly larger diameter than the more insensitive explosives. Cast TNT does not initiate properly near the edge of the cavity, the useful diameter being less than two-thirds of the total.

The donor can be made of any high explosive, if an adequately sensitive booster pellet is placed at the point of initiation. However, it is an advantage to use the highest practical detonation velocity to minimize arrival differences of the detonation wave through the donor. Also, the donor can be made thinner and still give an adequate velocity to the transfer plate.

The amount of time that must be compensated for by the transfer plate and cavity depends on the donor thickness and diameter and the detonation velocity through it. For a 1-in.-thick, 4-in.-diameter pentolite donor this time difference is about 4 μsec. For a 3/4-in.-thick, 10-in.-diameter 75/25 cyclotol donor it is about 13 μsec.

INITIAL CAVITY CALCULATIONS

An approximate profile for the cavity can be calculated by making a number of simplifying assumptions. First, the donor is initiated at a point on its surface. Second, the detonation wave is instantly and isotropically propagated in the donor. Third, since the transfer plate is thin, the shock wave in it can be assumed to be either unretracted or travelling normally to its own surface without a serious difference. Fourth, the free surface velocity of the transfer plate is constant across the gap and is the same at any radius. Fifth, the impact of the transfer plate against the acceptor produces a full detonation velocity without a delay. The resulting cavity contour is nearly parabolic.

The booster can then be tested for deviation from simultaneity.

This is easily done with a high-speed streak or smear camera, the defining slit of the camera being aligned across the flat face of the acceptor. When the time deviation is known the cavity can then be fully corrected to give a plane wave in one or two tries.

CORRECTING THE CAVITY PROFILE

In making a cavity correction both the instantaneous transfer plate velocity and the acceptor detonation velocity are used. The relation is

$$\Delta S = \frac{D \cdot U_{f.s.}}{D - U_{f.s.}} \cdot \Delta t$$

Where ΔS is a change in cavity depth and Δt is the corresponding time deviation from simultaneity. It is best to make the correction relative to the bottom of the cavity rather than the edge, since the latter has some delay in initiation.

There are a number of reasons why the actual required profile deviates from the calculated one. The more important are: the point of initiation is not a true point; the detonation velocity in the donor does not propagate isotropically; the transfer plate motion is rather complex, accelerating in jumps; and the acceptor explosive does not initiate immediately on impact with full detonation velocity.

VARIATION OF THE DONOR THICKNESS

Figure 2 demonstrates the effect of varying the donor thickness in one particular transit plate-acceptor arrangement. The donor was of cast 50/50 pentolite and had a 4-in. diameter. The steel transfer plate was 0.180 in. thick. The arrival of the detonation through the Composition B acceptor was recorded by a smear camera, time progressing to the right. The cavity shape used was that designed for a 1-in. unconfined donor.

For the 1-in.-thick donor, the ratio of the donor to the transfer plate thickness, H_e/H_m, is 5.56. This is the donor thickness for which the cavity is correct. The time spread over the 4-in. diameter is less than 0.1 μsec. The difference in the detonation wave transit through the donor, from center to edge, is 4.2 μsec. The average velocity of the transfer

plate over the center of the gap is about 1000 m/s. The 3/4-in. donor, $H_e/H_m = 4.17$, is delayed in the center by 0.5 μsec. The apparent velocity of the transfer plate is 830 m/s. The time difference through the donor is 4.7 μsec. The 1/2-in.-thick donor, $H_e/H_m = 2.78$, is delayed by 1.5 μsec, the apparent plate velocity being about 660 m/s. The time difference through the donor in this case is 5.3 μsec.

THE EFFECT OF DONOR CONFINEMENT

When the 1/2-in.-thick, 4-in.-diameter donor ($H_e/H_m = 2.78$) is backed by a 3/8-in. steel plate as shown in Figure 3, the arrival of the detonation through the acceptor is greatly changed from that of the unconfined condition. The detonation through the acceptor is ahead in the central region, the time spread being 0.43 μsec over the 4-in. cavity. In the unconfined case it was delayed by 1.5 μsec. If the donor is thick enough, i.e., if H_e/H_m is greater than 5.5 for pentolite-steel, the effect due to the steel backing of the donor is very slight. The time spread is 0.18 μsec as compared to 0.10 μsec for the unconfined donor which is shown in Figure 2. As before, the cavity was that designed for a 1-inch unconfined donor.

When the same booster as above is heavily confined in a steel cylinder and the donor backed as before, there is only a slight change in wave shape. There is somewhat better initiation at the edge of the cavity, making the effective diameter of the confined booster slightly greater than for the unconfined booster.

TRANSFER PLATE THICKNESS VARIATION

The effect of changing the transfer plate thickness on the arrival of the detonation wave through the acceptor is shown in Figure 4 for a given donor-acceptor arrangement. The cavity diameter was 8.5 in. The transfer plate was of mild steel. The cavity profile was originally based on a 1 1/2-in.-thick donor. In the examples shown it was used with a 1-in.-thick donor. Any reasonably smooth, approximate profile can serve as a basis for comparison. The results of three different transfer plate thicknesses are shown. The time trace of the 0.114-in.-thick plate shows that it requires a much deeper cavity than do the other two thicknesses. A comparison between the 0.185-in.- and 0.242-in.-thick plates indicates that a much simpler correction would be necessary for the former, since the

latter has a peculiar configuration in the center.

PELLET VARIATION IN THE DONOR

Figure 5 shows that some control over the arrival of the transfer plate in the central region of the acceptor can be achieved by the choice of the small pellet at the detonator. These tests were made with a 10-in.-diameter, 3/4-in.-thick donor and a 3/16-in.-thick transfer plate. When the detonation velocity is considerably lower in the pellet than it is in the donor, as in the case of tetryl in cast 75/25 cyclotol, a delay occurs in the arrival of the detonation through the center of the acceptor. This amounts to 0.55 μsec for the example shown. If an 1/8 in. layer of tetryl is placed over the 75/25 cyclotol donor, the plate arrives early by 0.50 μsec in the center. The condition of equal detonation velocity in the pellet and donor is about optimum when the pellet is flush with the donor surface. The slightly early arrival, relative to the neighboring region, is probably due to the explosive column formed by the detonator.

SCALING RELATIONS FOR H_e/H_m = 5.56

Scaled profiles of three boosters of different dimensions are shown in Figure 6. The ratio of the difference between depth of the cavity at radius R and its maximum depth to donor thickness is plotted against the ratio of R to donor thickness. The ratio of donor to transfer plate thickness is held constant at 5.56. The donors are all cast 50/50 pentolite and the transfer plates are mild steel. The solid line is the curve for a 1-inch donor, the cavity diameter being 8.5 in. This curve is based on a correction applied to the 0.185-in. transfer plate arrangement shown in Figure 4. The dotted curves are for an 8.5-in.diameter booster with H_e/H_m = 1.50 in./ 0.270 in., and a 4-in. diameter with H_e/H_m = 1.00/0.180 in. The smaller the relative diameter, the more complex the cavity profile becomes.

It can be concluded that if H_e/H_m remains the same, the contour of the cavity, relative to the bottom, will be similar over comparable radii, except for the deviation indicated by the dotted curves. Also, geometrically and materially similar boosters will have essentially similar cavity contours.

MODIFIED NOL PLANE WAVE BOOSTERS

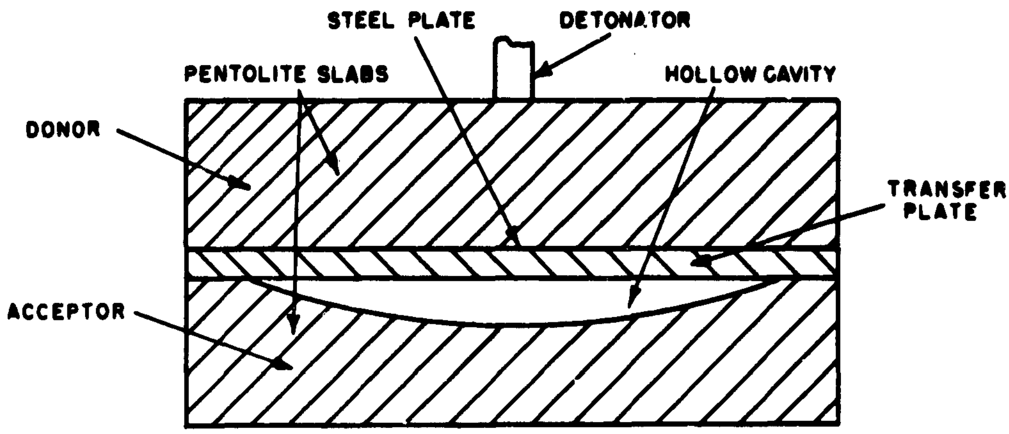
There are several general shapes that the components of the NOL-type lens may take other than the one already described. The transfer plate may be curved, forming the cavity on a flat acceptor, or both the transfer plate and the acceptor may be curved, the concave surfaces facing each other. Another modification consists of a variable thickness transfer plate, a constant thickness gap over which it travels, and a flat acceptor. The transfer plate is thickest at the center, giving a low free surface velocity relative to the edge. The shaped boundary faces the donor.

A booster of the latter type has been tried which has a 0.75 μsec time deviation, being late in the center. It is believed that this can be corrected to less than 0.1 μsec. The steel transfer plate was made conical for simplicity, the edge being 0.125 in. thick and the center 0.250 in. The donor was 75/25 cyclotol, 1.00 in. thick at the edge and flat on the detonator side. The gap was 0.50 in.

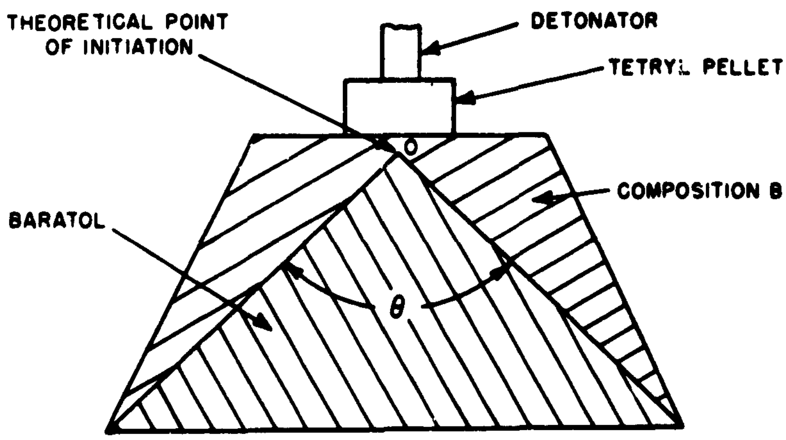
CONCLUSION

It is thus seen that the NOL-type booster is quite flexible in design. Boosters of the design shown in Figure 1 (top) have been developed from 1 5/8-in.- to 10-in.-diameters. The maximum deviation from simultaneity, for 1 5/8-in.-to 6-in.-diameter boosters, over the useful diameter, is about 0.1 μsec. The deviation for the 10 in. diameter is 0.25μsec. It is quite possible that by carefully selecting the booster components and by firing under stable temperature conditions, these deviations can be reduced by one-half or more.

It can be seen that both confinement and placement of booster pellet near the detonator affect the transmitted wave shape. A design must therefore be tested under conditions nearly similar to those to be encountered when the wave-shaping device is used. This is particularly important when the donor explosive layer is thin. Donor layers as thin as 3/8 in. have proven entirely satisfactory when the explosive is 50/50 pentolite, cyclotol containing fine grain RDX, or an octol (HMX/TNT) containing fine grain HMX. Particle size for the RDX or HMX should be about 70 microns, maximum, to assure good propagation of detonation in the donors.

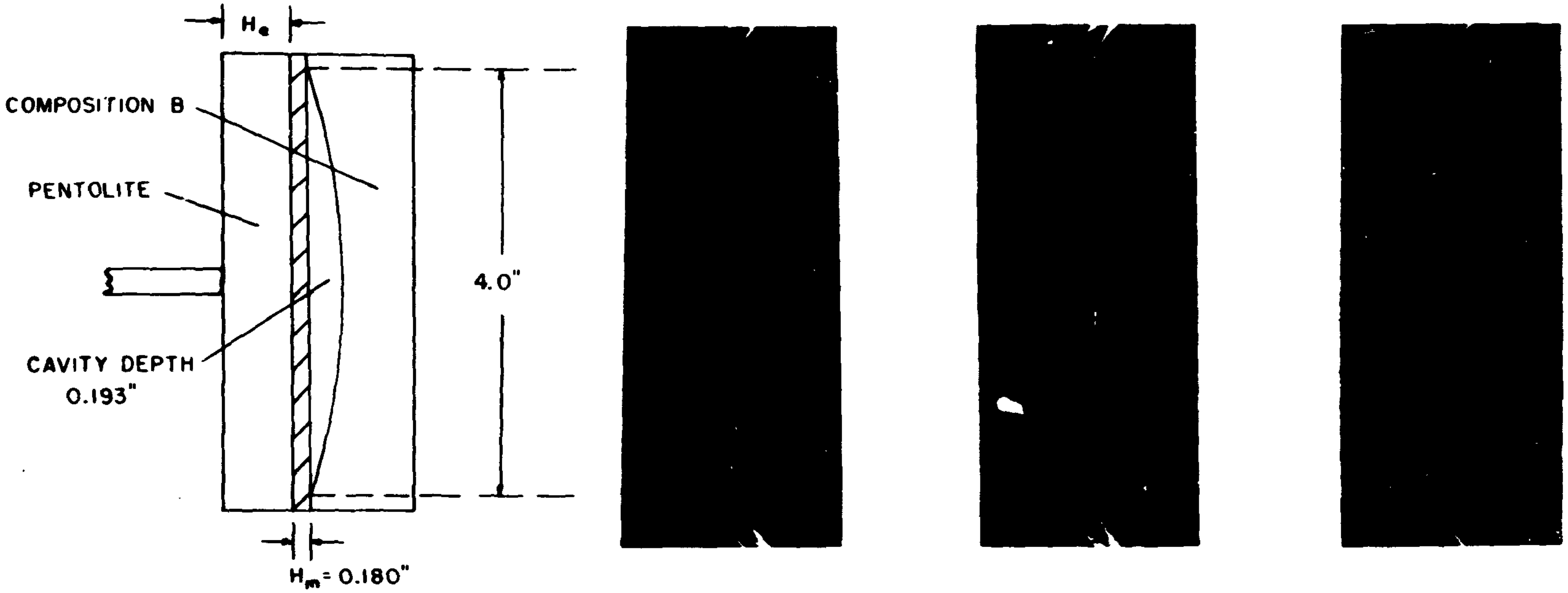


CROSS-SECTIONAL VIEW OF THE NOL PLANE WAVE BOOSTER



CONVENTIONAL PLANE WAVE BOOSTER

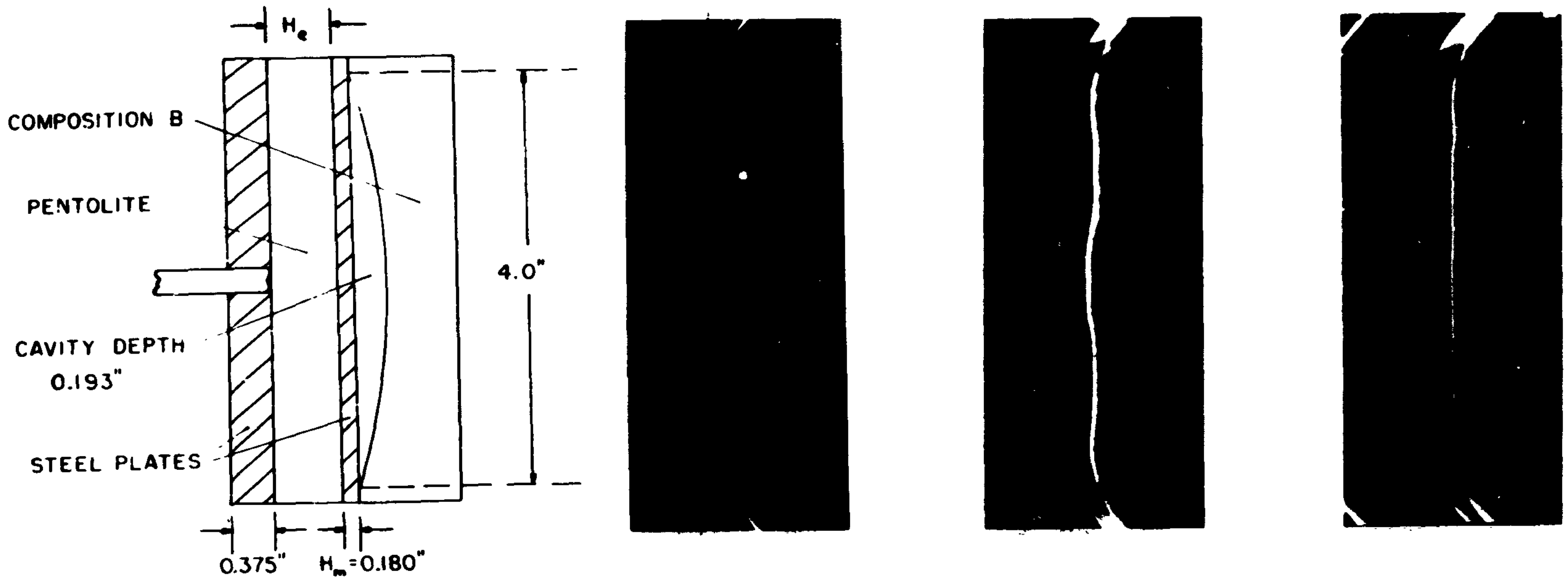
Figure 1



TIME →

SPREAD	0.1 μ SEC	0.5 μ SEC	1.5 μ SEC
DONOR THICKNESS	1.00"	0.75"	0.50"
RATIO H_e / H_m	5.56	4.17	2.78

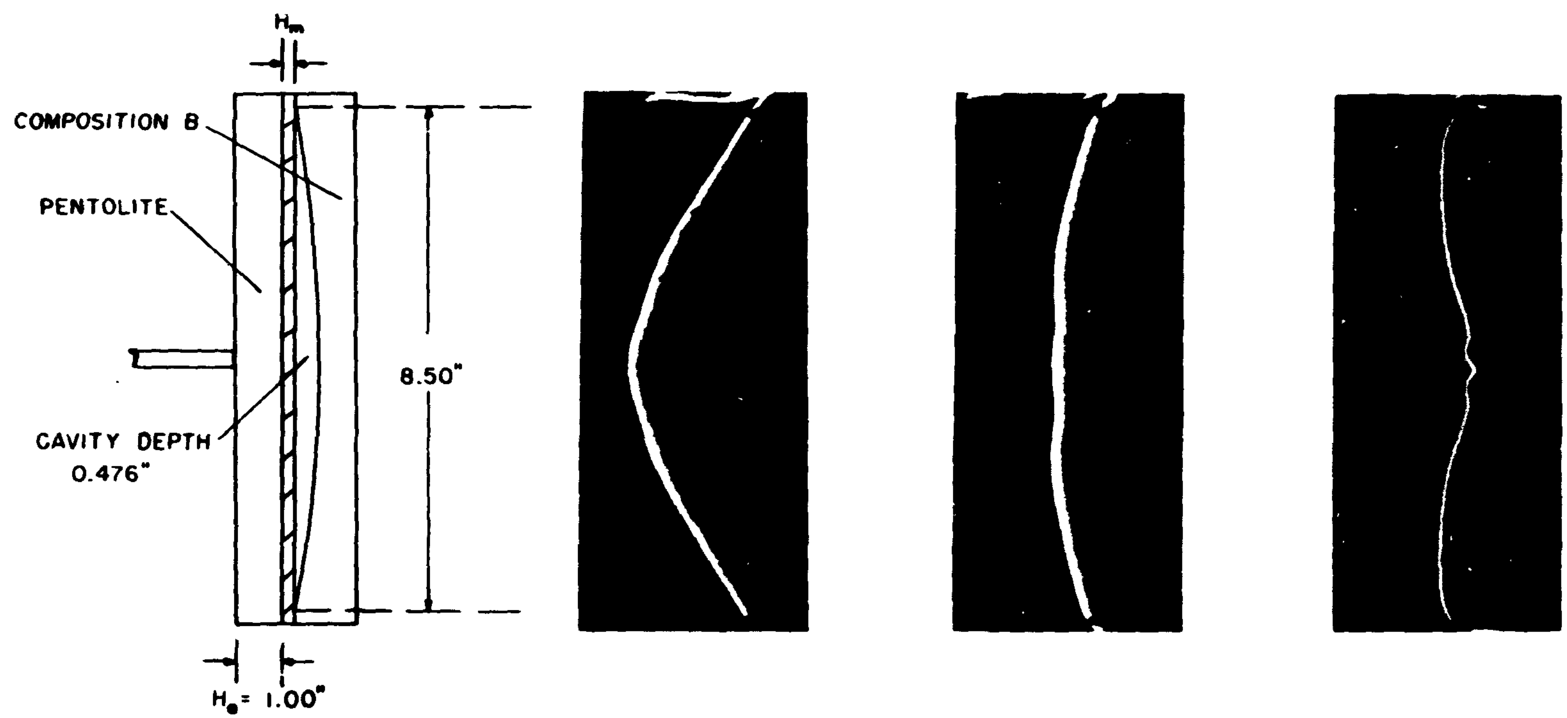
Fig 2 Donor Thickness Variation Effect



TIME →

SPREAD	1.50 μ SEC	0.43 μ SEC	0.18 μ SEC
DONOR THICKNESS	0.50"	0.50"	1.00"
CON INEMENT	none	0.375" Steel	0.375" Steel
RATIO H_e/H_m	2.78	2.78	5.56

Fig 3   Donor Confinement Effect



	TIME		
SPREAD	4.1 μ SEC	1.3 μ SEC	1.1 μ SEC
STEEL PLATE THICKNESS	0.114"	0.185"	0.242"
RATIO H_e/H_m	8.77	5.41	4.13

Fig 4 Transfer Plate Thickness Variation Effect

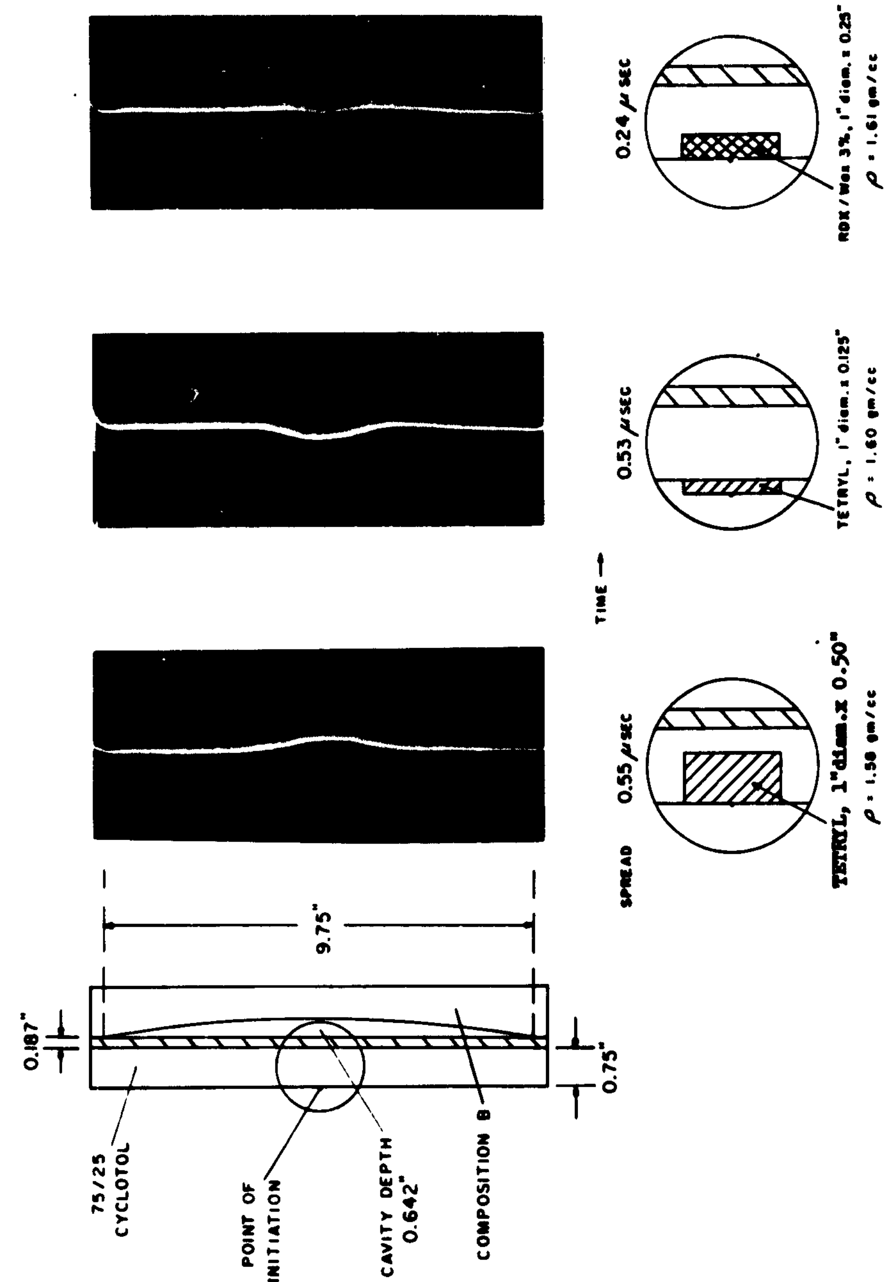


Fig 5 Pellet Variation in Donor

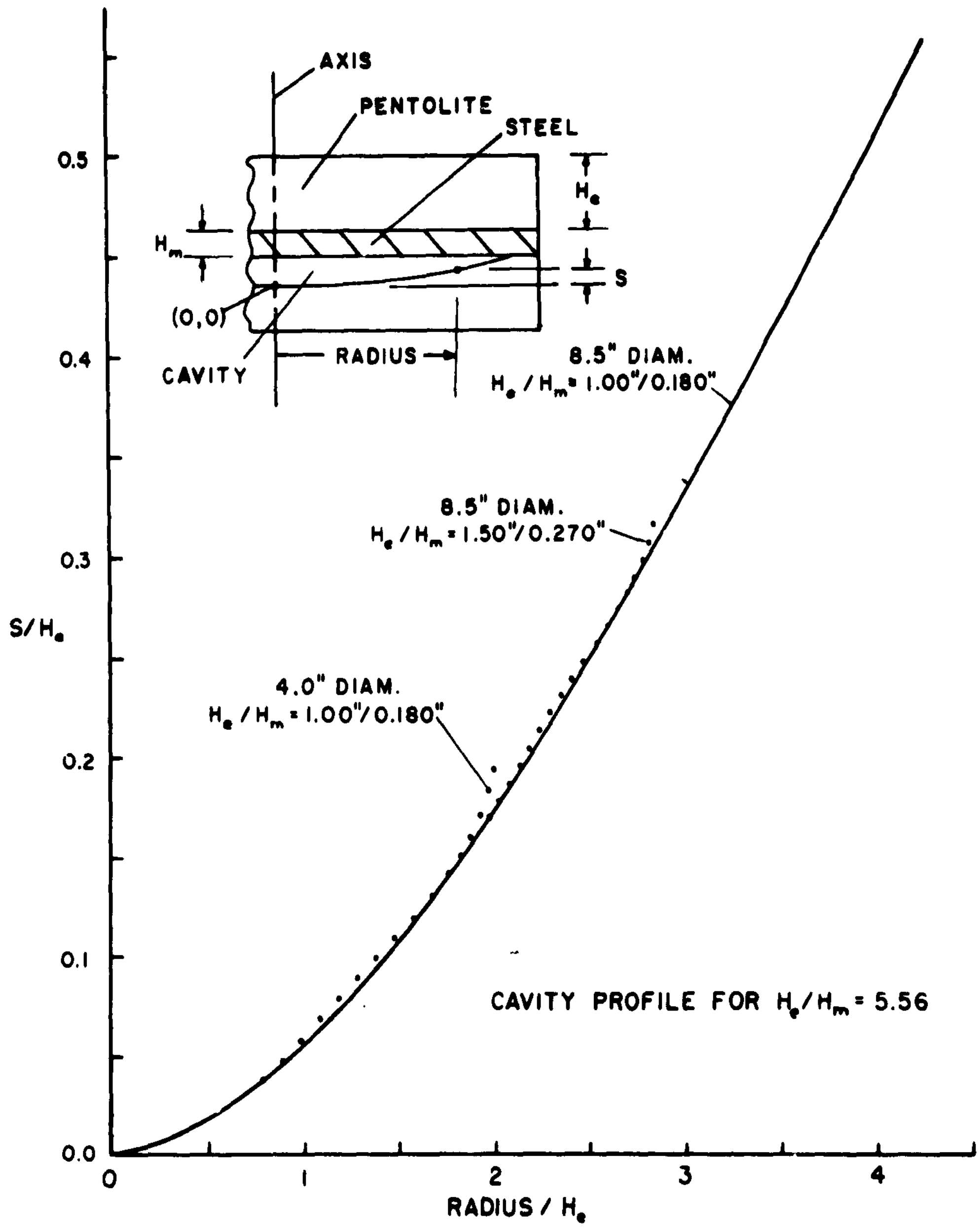


Fig 6 Scaled Profiles of Three Boosters

THE APPLICATION OF WAVE SHAPING

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INTRODUCTION

Wave shaping may be applied to the shaping of the detonation front in an explosive, or the shaping of an explosively induced shock pulse in gases, liquids, or solids. Since the detonation of an explosive is a true shock-pulse phenomenon, it is sometimes easier to investigate some properties of detonation by using shock pulses in some inert medium rather than working directly with explosives. It is likewise sometimes easier to accomplish a specific result by means of explosively induced shock pulses than it is by the detonation front directly. Wave shaping may be used (1) to develop some directional effect, (2) to modify the shape of the explosively induced shocks in inert media, (3) to effect the direction of motion of solids, (4) to effect the velocity of materials, (5) to effect the detonation rate, (6) to tailor the jet of a shaped change for a specific target, and (7) as a research tool.

THE APPLICATION OF WAVE SHAPING TO DEVELOP DIRECTIONAL EFFECTS

Shocks in Gases

Here, for the most part, detonation front shaping is a second-order effect. A cubical charge detonated from the center will give a shock pulse intensity distribution with maxima normal to the faces of the cube. This is particularly noticeable from the shock pulse intensities in air as observed from a distance. This can be detected most easily by centrally detonating at 0.2-second intervals two cubical charges of about 2 or 3 inches on a side at a distance of a quarter of a mile or greater. If these charges have top and bottom faces horizontal but are rotated 45 degrees to each other on a vertical axis, and two observers, also spaced 45 degrees apart, such that observer A is normal to the face of charge No. 1 and in line with the corner of charge No. 2, and observer B is normal to the face of charge No. 2 and in line with the corner of charge No. 1, the sound reaching the two observers will be reversed in intensity. The sound from charge No. 1 will be loudest at observer A, whereas the sound from charge No. 2 will be the loudest at observer B, and by a rather large factor.

If we now set up two charges with the same orientation and have the observers spaced at 90 degrees but this time detonate the charges by means of thin plane waves, with observer A normal to plane wave generator on charge No. 1 and 90 degrees from it on charge No. 2, and the reverse for observer B, a smaller difference in the intensity will be observed than in the previous case, the difference will still be appreciable.

If you therefore want to create a maximum disturbance at a moderate distance with a given total quantity of unconfined explosive, a vastly better job can be done by shaping the charge and using point initiation rather than detonation front shaping. The maximum effect would be produced by a circular sheet of explosive detonated from the center and having the minimum thickness in which detonation will propagate and at the same time having this sheet of explosive formed into a very wide angle cone of about 150 degrees. This, however, is wave shaping but it is shaping the wave in the air and not in the high explosive.

There is, however, still another technique for producing an effect at a distance but at a rate of travel which is much slower than a shock phenomenon. It is, therefore, intermediate between a projectile and a wave motion. In the case of a projectile the missile travels the entire distance from the charge to the target, whereas in the case of a wave motion the actual transport of material is over a relatively short distance. In the phenomenon to which I refer, the effect reaches the target much later then the arrival of the shock wave. However, it is an actual impact of a mass of gas, although the gas striking the target contains little if any of the gas leaving the vicinity of the explosive. I refer to the phenomenon known as a toroid, such as a smoke ring.

If a cylindrical charge is detonated along the axis of a steel cylinder open at one end, and the charge used is short as compared to the length of the cylinder, and is placed near the closed end of the cylinder, a very intense toroid will result. Such a charge four feet long and weighing ten pounds was fired in a vertical explosion chamber 10 feet in diameter and 10 feet in height. This charge was photographed both by a still camera and a moving picture camera at 64 frames per second, and a sound recording was made of it.

As the blast and toroid emerge from the chamber, considerable light is,

of course, emitted and continuing out of this flash of light is the luminous toroid. The toroid rapidly loses its luminosity but contains enough smoke to be visible for several seconds. Beyond this it is invisible although it is distinctly audible for a period of one minute. Some study was made of this phenomenon during the war with the hope of using it for knocking down low-flying planes, but nothing of any consequence ever developed from it.

Shocks in Liquids

High-intensity shocks in liquids can be photographed very well by means of the framing camera and backlighting with parallel light. Figures 1 and 2 are a series of framing camera pictures taken at 1-μsec intervals. The explosive extends from the left-hand edge to the center of the picture over the top of the inert material above the liquid. The shock pulse in the liquid is essentially straight until it reaches the boundary between the explosive and the inert material, at which point it progresses radially. Figure 3 shows a spherical shock pulse passing through two liquids of different density and a reflection at the interface. The transmission of shock pulses through liquids and the spall of the surface of the liquid (Fig 4) provides an excellent method of determining the equation of state of the liquid.

The velocity of the detonati[illegible] the explosive across the bottom of the liquid is measured by probes a[illegible] raster scope. The velocity of the shock pulse in the liquid is obtained from the shock pulse angle in the liquid, and the particle velocity by the angle of the spalled liquid at the surface.

Shocks in Solids

The development of very strong shocks in solids is one of the very effective ways of using high explosives. Although steel is the metal with which we are most commonly concerned, its behavior is probably less like most of the metals than any of the common metals. Two factors are responsible for this: the elastic-pulse velocity in steel travels faster than a shock pulse, and there is a change of phase which occurs at pressures of 131 kilobars or about 2,000,000 psi. For this reason the shock pulse pressure in an explosively induced shock is very quickly reduced to 131 kb; however, below that pressure the attenuation is only about 25% per inch of travel. While this imposes several limitations in some instances, it at the same time provides an excellent research tool in the study of shock pulses.

The manner in which the detonation rate of the explosive is reflected in the behavior of metals when subjected to explosively induced shocks provides a key to the solution of some munition problems. If 2-inch-diameter sticks of explosive 4 inches long and having different detonation rates are placed on 6-inch-square pieces of ¼-inch-thick mild steel, and detonated from the top, the results (Fig 5) will show a striking correlation to detonation pressure. The detonation rate of the explosive on plate A was 2 mm/μsec, on plate B 4 mm/μsec, on plate C 6.5 mm/μsec, on plate D 7.4 mm/μsec, and on plate E 8.1 mm/μsec. The shock pulse velocity in the steel is 5 mm/μsec and it will be observed that in those cases where the detonation rate is less than the shock pulse velocity the plates are merely deformed, whereas in those cases where the detonation rate exceeds the shock pulse velocity the plates are perforated. It will also be observed that the maximum damage occurs to the plate when the detonation rate is only slightly above the shock pulse rate.

If a cylinder of steel 3 inches in diameter and 6 inches long is completely encased in a ¼-inch sheath of explosive and the explosive is simultaneously detonated from both ends, there will be a band around the center (Fig 6), in the center of which is a very narrow groove along which the detonation fronts meet. If this cylinder is sectioned (Fig 7) a large cavity containing a loose piece of steel will be found in the center. The cut in the plane of the meeting of the detonation fronts will have smooth faces. If now a band of explosive is removed in the zone where the two detonation fronts met, there will be little or no cut in this plane, but the remainder of the cavity will be only slightly affected. On the other hand, if two cylinders only half as long are placed with two smooth machined faces in contact in the middle and the sheath of explosive is continuous, the cavity will be formed in the center minus the loose piece of metal. If the plane of the transverse cut exactly coincides with the joint between the two pieces of metal, no marks will occur on the metal faces. However, if the points of initiation are at a slight angle so that the transverse cut in the plane of the meeting of the detonation fronts intersects the boundary between the two pieces of steel, the smooth faced cut will occur (Fig 8) even though it is only a few thousandths of an inch below the surface of the metal. If a band of explosive is placed around a bar of steel and detonated at diagonal points, it will cut the bar at an angle (Fig 9) and in the plane where the detonation fronts meet. Taking advantage of this effect, Sid Moses of the Poulter Laboratories has developed a series of diamond-shaped charges for

demolition purposes. If such a charge is wrapped half to two-thirds the way around a bar with the long diagonal of the diamond charge parallel with the bar and simultaneously detonated at the twoendsof this diagonal so that the detonation fronts meet in a plane normal to the bar, steel bars (Fig 10) up to 8 or 10 inches in diameter can be cut with fantastically small quantities of explosive. If a 3-inch-diameter steel bar 18 inches long has a 0.027-inch diameter hole drilled along its axis and a 5-inch-long section of this hole is loaded with C-3,(this will require about 12 grams of explosive), detonating both ends of this 5-inch-long column of explosive simultaneously will completely sever the bar in the plane where the detonation fronts meet. This provides a shear pin which will support a terrific load with precision timing. Such a shear pin has been extensively used in some drop tests involving up to 200 tons. The meeting of detonation fronts provides an excellent control for the cutting of steel on other materials. Figure 11 is the result of detonating a $\frac{1}{16}$-inch-thick layer of C-3, on the face of a smooth 8-inch-diameter, ½-inch-thick steel plate, with no scoring in either the plate or the explosive. The explosive was simultaneously detonated from 19 points and the cutting occurs along the boundaries where the detonation fronts met.

THE EFFECT OF WAVE SHAPING ON SPALLING

Since the spalling of metal from one face of a metal plate as a result of the detonation of an explosive on the opposite face is a result of the shock pulse being transmitted through the plate, it would be expected that wave shaping should have a marked effect, and such is the case. If a 12-inch-diameter sheet of explosive ½-inch thick is placed in contact with a 3-inch-thick plate of mild steel, and point detonated from the center, a spall of uniform thickness and having a slightly larger diameter than the explosive charge will be thrown off the opposite face. If the charge is detonated from one edge, the spall will be similar to the one produced by the centrally initiated charge, but will be displaced in the direction that the detonation traveled across the plate, and by a distance approximately equal to the thickness of the plate. Frequently a small piece will be missing from the otherwise circular spall and from the edge where the charge was initiated.

If now the charge is peripherally initiated, the spall will be circular, thin at the edge, and will extend about 2.5 inches into the 3-inch thick plate at the center. Since the spall is controlled largely by the time-

pressure profile of the shock pulse, the thickness of the spall from a given explosive charge can be increased by increasing the confinement of the charge

The theory of spalling is quite well understood, but is beyond the scope of this paper. The "squash" head projectile or HEP shell is perhaps the outstanding example of this type of munition and its performance could be enhanced through the control of the point of initiation and a peripheral initiation of the charge.

WAVE SHAPING AND DIRECTION OF MOTION OF A SOLID

The direction of propagation of a solid in contact with an explosive charge is again dominated primarily by the orientation of the explosive-solid interface rather than by any shaping that can be given to the detonation front. In this case we are primarily interested in two things, the direction of motion imparted to the solid and the velocity which it acquires. A very good qualitative illustration of the orders of magnitude of these effects can be demonstrated by a lined cavity charge in which the steel liner is ⅛-inch thick and has a spherical radius of curvature of 4 inches. If the charge is peripherally detonated, the liner will pass through a 1-inch-diameter hole at a distance of 25 inches and along the axis of the charge. If the charge is point initiated at the center, the liner will pass through about a 2.5-inch-diameter hole at a distance of 25 inches and along the axis of the charge. If the charge is point initiated from one edge of the liner it will pass through about a 2.5-inch-diameter hole at 25 inches, but displaced from the axis away from the point of initiation by about 2.5 inches.

There are several factors which combine to determine the direction of motion that will be imparted to a solid material in contact with an explosive. If the detonation is propagating in a direction parallel with the exsive-metal interface (Fig 12) the direction of motion of the metal will be controlled primarily by three factors. These factors are, in order of decreasing importance, the orientation of the explosive-metal interface, the differential displacement of the plate due to difference in arrival time of the impulse as the detonation front passes along the interface, and the direction of motion of the particle velocity in the detonation front.

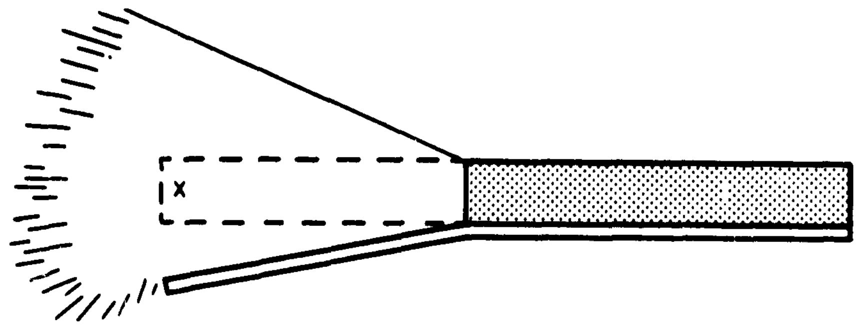

Fig 12 Detonation Propagating in Direction Parallel with Explosive-Metal Interface

The initial and instantaneous v 'ocity imparted to the plate will be almost normal to the explosive-metal interface, with possibly a very small deflection due to the direction of motion of the particles in the detonation front. If the detonation front is not parallel with the explosive-metal interface, that portion contacted first by the detonation front will start moving first and therefore develop an angular displacement of the plate. If there is any appreciable variation in impulse this might accentuate, minimize, or even cancel this angular displacement. As soon as the plate assumes a position which makes an angle with its original position, the pressure against the plate in its new position will accelerate in a direction normal to its new position and thereby develop a velocity component in the direction of travel of the detonation front or increase in impulse across the surface of the metal plate.

Since the development of a uniform impulse plane wave by members of the staff of the Poulter Laboratories, a series of experiments has been outlined (Fig 13), but not yet carried out, whereby both the velocity and the direction of the plate can be studied as a function of the angle between the detonation front and the explosive-metal interface. Such an arrangement permits the development of a detonation front in explosive charge B at angle β merely by changing the angle α and detonation from either (1) or (2).

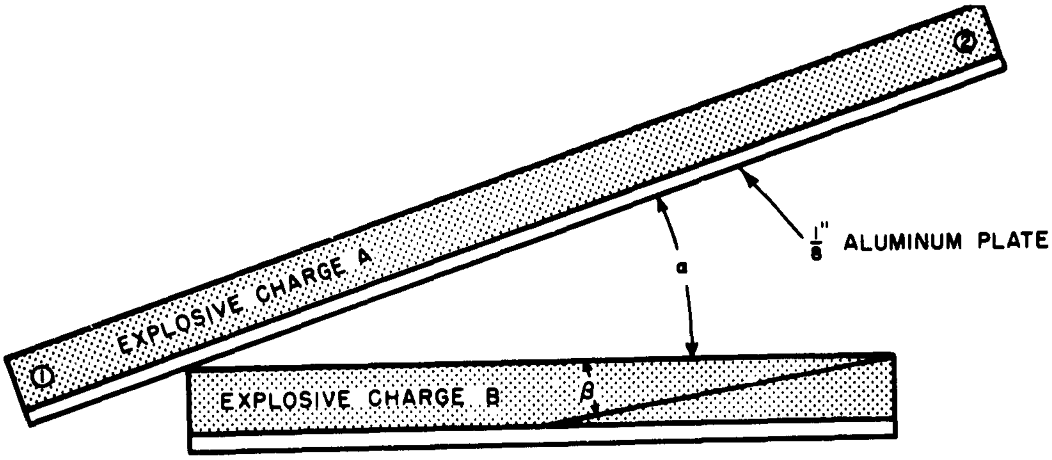

Fig 13 Experiment for Studying Effect of Angle between Detonation Front and Explosive-Metal Interface

It is not surprising therefore, that point initiation from one edge of the liner displaces the jet by about 2.5 inches at a distance of 25 inches. The most important difference, however, is the target penetration at that distance. In the case of peripheral initiation the liner will penetrate 10.5 inches of steel. In the case of the point initiation the penetration drops to 2 inches of steel, or only about 20% of the penetration obtained by peripheral initiation.

WAVE SHAPING AND VELOCITY OR IMPULSE

While the penetration has dropped off to only about 20% of the peripherally initiated value, this does not mean that the velocity has been reduced to one-tenth. A more reasonable figure would be a reduction to about one-third. There are two primary factors which determine the plate velocity as a function of the orientation to the detonation front. Consider the two extremes (Fig 14, a and b). In (a) the explosive is detonated simultaneously over its entire upper surface, whereas in (b) it is detonated at one end and travels from left to right. In (a) the relief pulse is traveling in a medium whose particle velocity is in the same direction as the detonation at points close to the detonation front and in the opposite direction at points somewhat removed from it.

In (b) the relief pulse following along behind the detonation behaves in

the same manner as the relief wave in (a); however, the relief wave originating at the surface of the explosive away from the metal plate is affected very little by the particle motion of the products of detonation. The time that the pressure is applied to the metal plate in (b) is therefore greater than it is in (a). However, the velocity in (a) is appreciably greater than it is in (b) because the pressure due to detonation, and the dynamic pressure due to the very high particle velocity in the direction of the plate, are directly additive. In other words, even though the time in (b) is appreciably greater, the pressure is enough greater in (a) to give it an appreciably larger impulse and, hence, velocity. Wave shaping may therefore be used to increase the impulse by increasing the pressure, its time of application, or both.

WAVE SHAPING AND DETONATION RATE

Another important way in which wave shaping may increase the impulse is through convergence. By means of the convergence it is possible to increase both the pressure and duration, and if the concave detonation front is allowed to travel a comparatively small radius of curvature it may increase the pressure by increasing the detonation rate. An increase of 20% in detonation rate will increase the detonation pressure by 2,000,000 psi.

From the relation that we have developed for the effect of radius of curvature upon the detonation rate

$$V_R = V_\infty \ e^{4.78/R}$$

Where V_R is the detonation rate at a radius of curvature R in mm, and V_∞ is the detonation rate of a plane detonation front, we find that a concave detonation front having a radius of curvature of 3 inches will have a detonation pressure 11% higher than for a plane detonation front, and 20% higher than for a convex detonation front having a radius of curvature of 3 inches. Even if the radius of curvature of the detonation front is crudely formed and the radius of curvature of the 7-inch liner is changed from 8 inches to 3 inches while maintaining the quantity of explosive constant, the average plate velocity and the penetration are very effectively changed, as shown in Table 1 and Figure 15.

The increase in plate velocity, as a function of the increase in the

detonation pressure resulting from the decrease in radius of curvature of the detonation front is calculated on the assumption that the time in the time-pressure impulse remains constant. The velocities would therefore be proportional to the pressures.

TABLE 1

100-Gram Liner

R (in.)	V_R	P (Kb)	Plate Velocity Calculated	Plate Velocity Measured	KE	Penetration, inches of steel
∞	7.91	500	5900	——	——	——
8	8.10	525	6200	8000	3.2×10^9	5.0
6	8.18	535	6320	8500	3.6×10^9	6.5
5	8.20	540	6380	9000	4.0×10^9	7.5
4	8.30	552	6520	10000	5.0×10^9	8.4
3	8.40	565	6660	12000	7.2×10^9	10.5

WAVE SHAPING IN LINED SHAPED CHARGES

Many attempts have been made to apply detonation front shaping to lined shaped charges, with varying degrees of success. Poulter Laboratories have made use of low-order detonation in the design of a special charge for use in perforating oil well casing. The specifications set up for this charge were that it develop a ½-inch hole in the casing instead of the $^3/_{16}$-to¼-inch hole developed by the conventional charge, that it operate at a very low standoff without reducing its penetration, that its penetration into the formation not be reduced, and that the quantity of explosive not be increased.

In order to meet these specifications, it would therefore be necessary that a jet be developed having a large mass at its forward end and at the same time maintaining a very high velocity gradient along the jet without reducing the velocity of the after-end of the jet. To put a relatively large mass of metal on the forward tip of the jet meant designing a cone having a large radius apex. This in turn meant developing an increased impulse for that portion of the jet if the velocity gradient was not to be disturbed, while at the same time maintaining the velocity of the after-end of the jet.

To prevent a discontinuity in the velocity gradient, or mass of metal along the jet, it was required that there be no marked discontinuity in the C/M ratio but, rather, a smooth gradation from apex to skirt of the cone.

The major problem therefore was to develop the necessary impulse for the apex portion of the cone to do two things: first, project a large portion of the metal of the apex of the cone into the jet, whereas in most conventional lined shaped charges the apex contributes a very small percentage of the jet material; second, give that large mass so high a velocity that the following portion of the jet does not overtake it in flight.

Peripheral initiation was investigated (Fig 16a) but this had six distinct disadvantages: (1) it developed a very high velocity jet containing a very small quantity of metal out along the axis of the cone, thus disrupting the accumulation of the desired mass of metal for the tip of the cone; (2) it tended to increase the quantity of explosive required in the charge to get good performance; (3) it tended to increase the length of the charge; (4) it necessitated a longer standoff distance for optimum performance; (5) it developed a smaller hole volume; and (6) it produced a highly developed slug which tended to follow through and plug the hole.

A charge was therefore designed which took advantage of the meeting of high- and low-order detonation fronts (Fig 16b). An attenuating barrier is placed in the after portion of the charge in such a manner that the shock pulse from the centrally initiated thin layer of explosive back of this barrier passes through the barrier and initiates low-order detonation of the rear central portion of the main charge. The high-order detonation travels out over the barrier, spreading the low-order zone laterally at a high-order rate, and converges upon the expanding low-order zone after going around the edge of the barrier.

A smear camera was used to follow the shape of the detonation front in these charges, and flash X-ray techniques to follow the formation of the jet and the particle distribution in the jet, and both the rotating disc and flash X-ray to study the velocity gradient along the jet. For the analysis of detonation front in the charge the liner was removed and a lucite plug having the same contour was inserted into the charge. This permitted the use of a multiple-slit system. The superposition of the high and low order over the apex of the cone is readily shown in the triple slit record (Fig 17), in

which the divided lines show the arrival of the low-order detonation at the surface of the cone about ¼ μsec before the superimposed high order converged upon it. The progress of the high-order detonation front down over the body of the cone is shown in Figure 18 using an eleven-slit system in the smear camera. The completeness with which the lucite prevents the smearing of adjacent traces is well illustrated in this figure. The experienced smear camera operator learns to take advantage of many tricks in order to obtain much useful data, such as the "ghost" grid of straight lines in the background of Figure 19, which serve as reference time marks.

The evidence that the development of a relatively large, dense mass of metal does form the forward tip of the jet and that the slug disintegrates into a number of small fragments is shown in Figures 20 and 21. The ring of fragments following each of the jets in Figure 21 is typical of all lined shaped charges. This represents an edge spall which is thrown off at the base of the cone but is usually obscured by other metal fragments in lined shaped charge flash X-ray pictures, or the picture does not extend far enough to include them.

The jet developed by this charge had the desired mass at the forward end, mass and velocity distribution along the jet, and almost completely disintegrated slug. The hole diameter in the 7/16-inch-thick steel casing was ½-inch, the penetration was equal to or greater than the conventional charge, and the hole volume was increased about threefold. The initial slug which is formed early produces the large hole through the casing and thereby creates the necessary standoff for the normal jet formation. For this reason a 1⅝-inch-diameter charge does not have its penetration impaired even with a standoff of less than ½ inch.

This charge design is equally effective for the conventional conical liner. Tests were run on ¾-inch outside diameter, 60-degree copper cones 0.020 inch thick and a ¾-inch-diameter charge of 5 grams. Penetration of as much as 4⅝ inches was obtained and the average was 4 inches for eleven shots with only a 1/16-inch steel case on the charge. A 5½-inch-diameter military charge which used a 45-degree steel cone 3/16-inch thick and a 12-pound charge was modified in the same manner. The modified charge contained only 6.6 pounds of hand-loaded C-3 in a 1/16-inch-thick steel case. The original charge developed a 2¾-inch to ¾-inch straight-taper hole 19 inches deep into a thick target, whereas the modified charge produced a 2¾-inch to ¾-inch hole diverging from a straight taper and 31 inches deep.

The most recently developed charge of this type is an eight-jet charge in which the jets are spaced at 45 degrees in a plane. The cones are 1 inch in diameter and contain 9 grams of explosive per cavity. These charges develop a $\frac{7}{16}$-inch hole in a $\frac{3}{8}$-inch-thick steel casing and penetrate 10 inches into a concrete target. Figure 22 is a night photograph of such a charge in which three small marker charges were spaced at 10-foot intervals in order to put a scale in the picture. For such a multiple-jet charge to function properly it is necessary that the detonation fronts travel out through all charges simultaneously to prevent interference between charges. These shaped charge developments have been jointly sponsored by Byron Jackson Division of the Borg-Warner Corporation and Welex Jet Services, Inc.

One finds many attempts in the patent literature[1] and elsewhere to apply wave shaping to lined shaped charges. One of the most common procedures is to use the optical technique of dividing the charge into concentric shells (Fig 23) of progressively lower detonation rate explosives. Even with a difference of almost 50% in the detonation rate between the first and the third shell, the actual wave-shaping effect indicated by the dotted lines from actual measurements is not very pronounced. The same patent discloses another technique (Fig 24) which represents a common misconception of being able to speed up or focus the energy of an explosive by inserting unlined shaped voids within the explosive. This probably originates from the spit-back type of fuse successfully used by the United Kingdom on certain shaped charges.

Except in very special cases, voids of this kind in an explosive charge merely tend to delay the detonation front rather than advance it. In fact, in this particular charge the technique had a very interesting effect, as shown in Figure 25, in that it developed a wavy detonation front.

Wave shaping of this type, wherein the explosive in contact with the metal liner has the lowest detonation rate, is not conducive to developing a high velocity in the jet. In fact, the performance of these charges, as would be indicated by the flash X-ray pictures (Figs 26 and 27) is far from spectacular.

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[1] Raymond Jasse, U. S. Patent 2,628,559, "Explosive Drill," February 17, 1953

THE APPLICATION OF WAVE SHAPING TO WARHEADS

It is sometimes desirable in the case of a fragmentation warhead to concentrate the fragments into planes, rings, jets, etc., under conditions where the outside shape of the warhead is fixed. Under these conditions about the only alternative is to use some type of wave shaping. If the contour of the warhead is convex, as is usually the case, the wave shaping must be greatly accentuated in order to compensate for the orientation of the explosive-metal interface and develop a reverse effect.

One of the most effective means of obtaining the extensive wave shaping required is through the use of a low-high-order lens. This is most effectively accomplished through the use of a steel barrier for controlling the initiating shock pulse intensity. This technique requires extensive development work before enough is known about it to do an effective job of designing without an extensive step-by-step experimental program. It does, however, have some very real advantages in that the lens can be made very thin, the wave shaping effects are very large, and it requires only a single uniform explosive.

USE OF WAVE SHAPING AS A RESEARCH TOOL

Perhaps even more important than the development of wave shaping for use in a particular munition is the application of wave shaping as a research tool. Many munitions may require wave shaping for best performance, but in any case the use of wave-shaping techniques will make possible a simple and better final design.

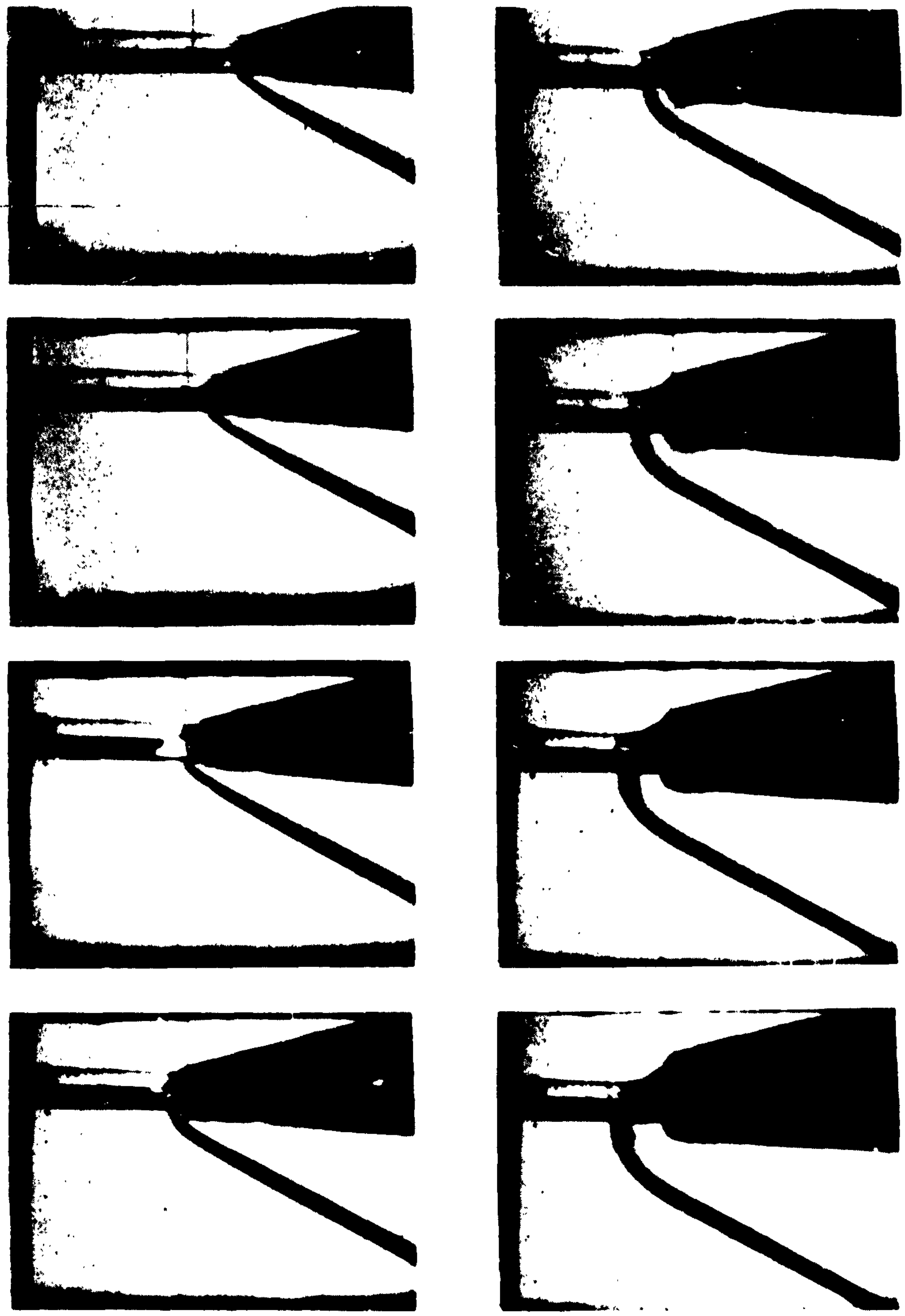

Fig 1 High-Intensity Shock in Liquid (1-μ sec intervals)

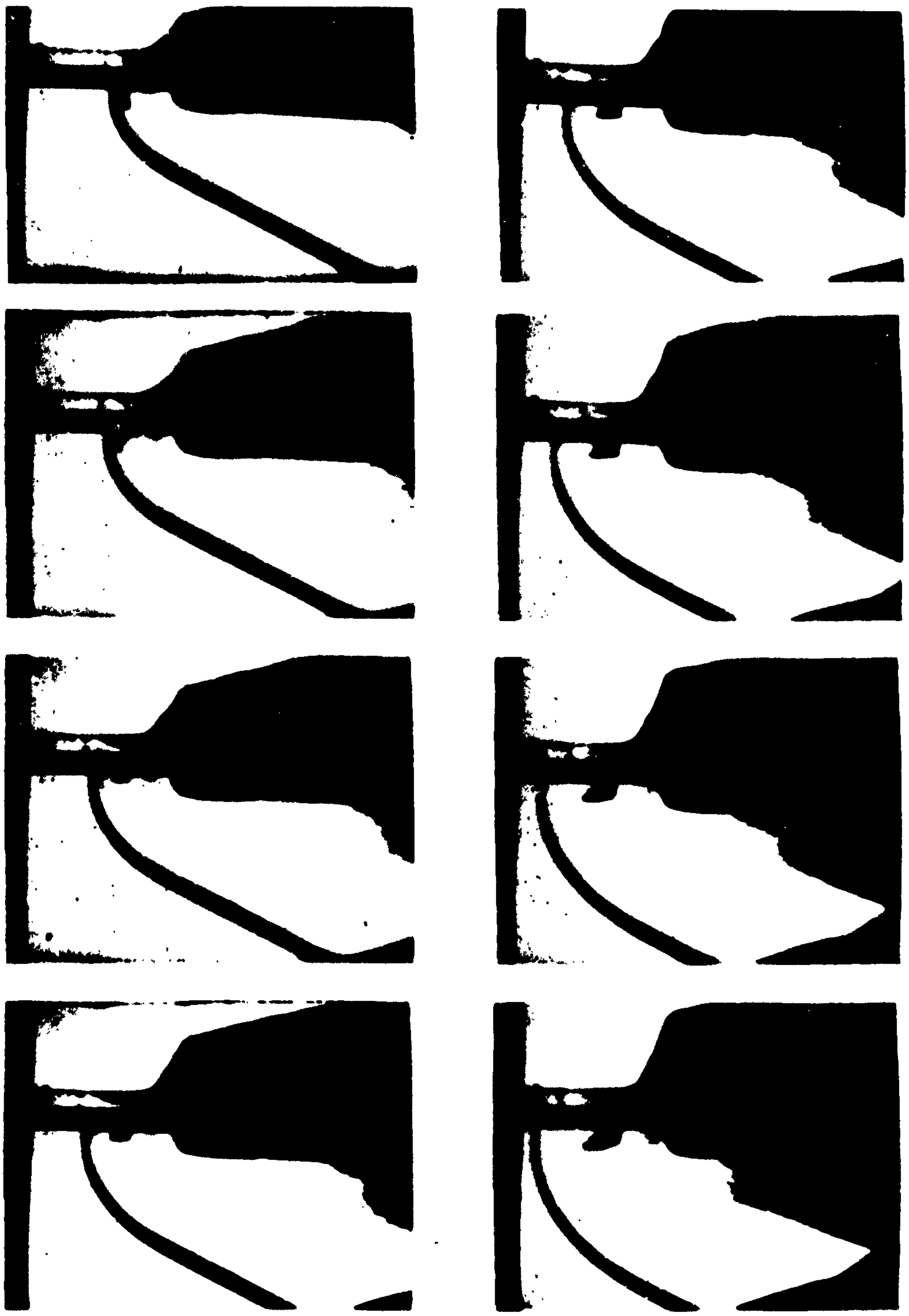

Fig 2 High-Intensity Shock in Liquid (1 – μ sec interval)

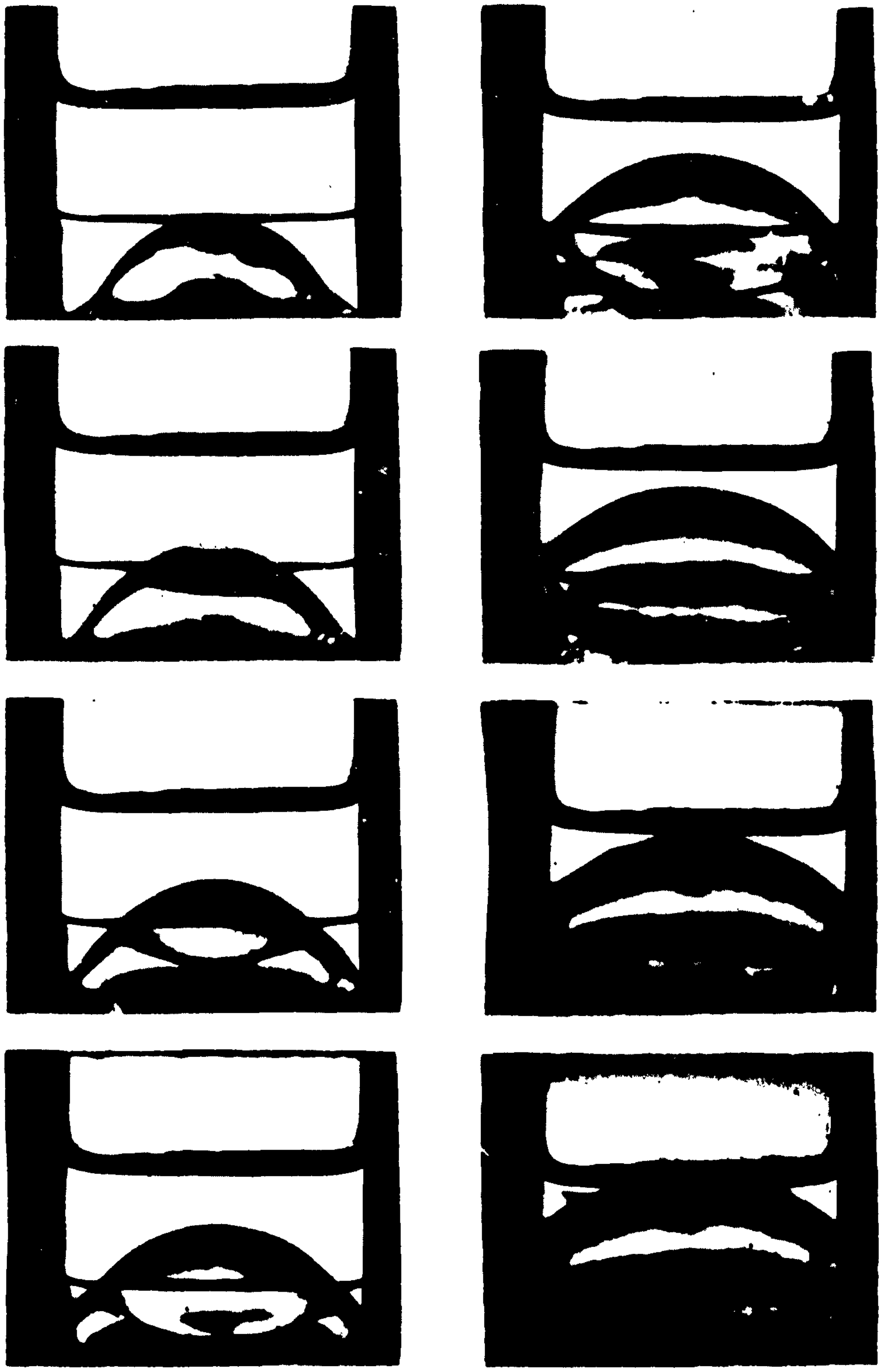

Fig 3 Spherical Shock Pulse Passing through Two Liquids of Different Density

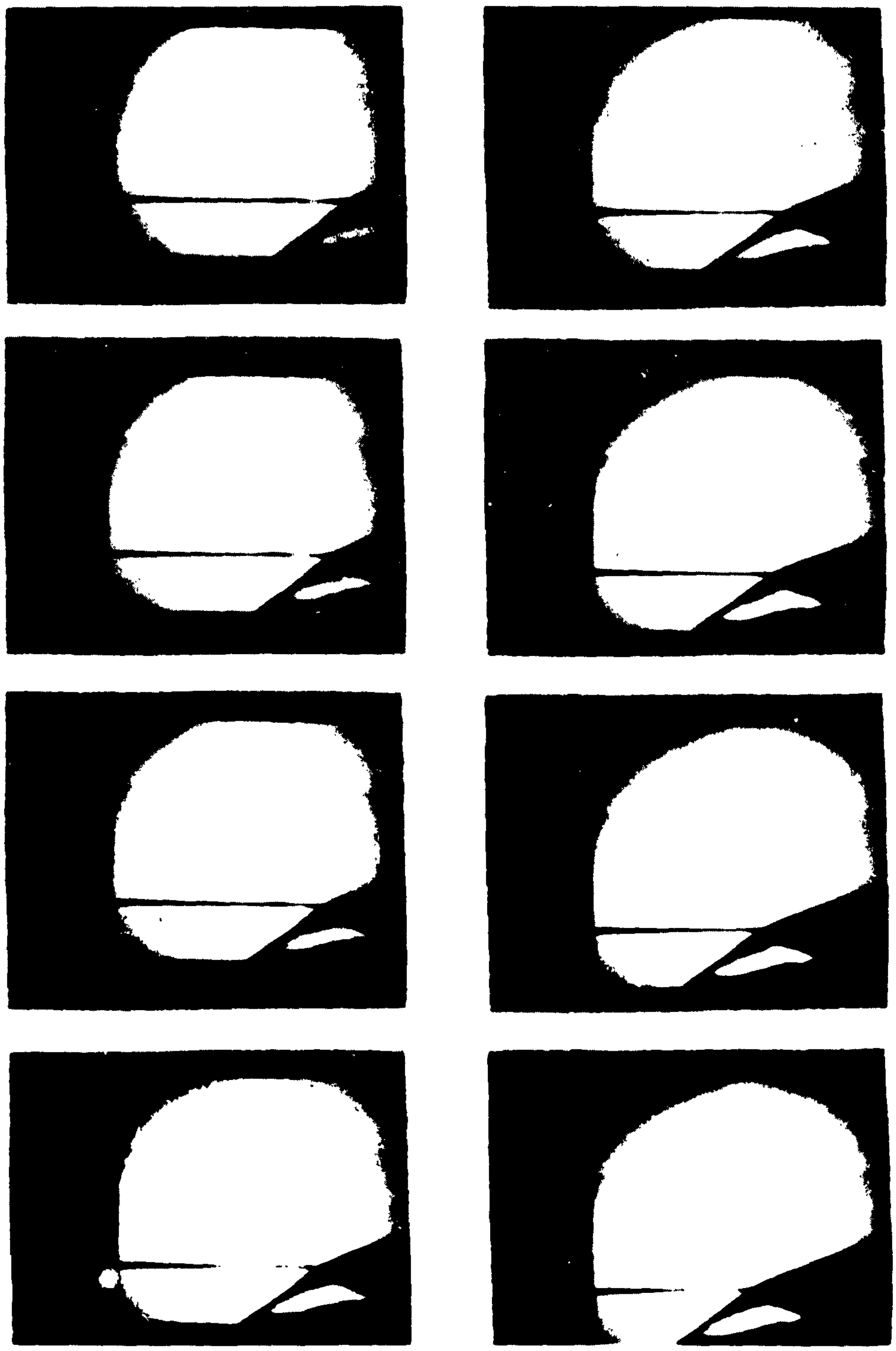

Fig 4   Spall of Surface of Liquid

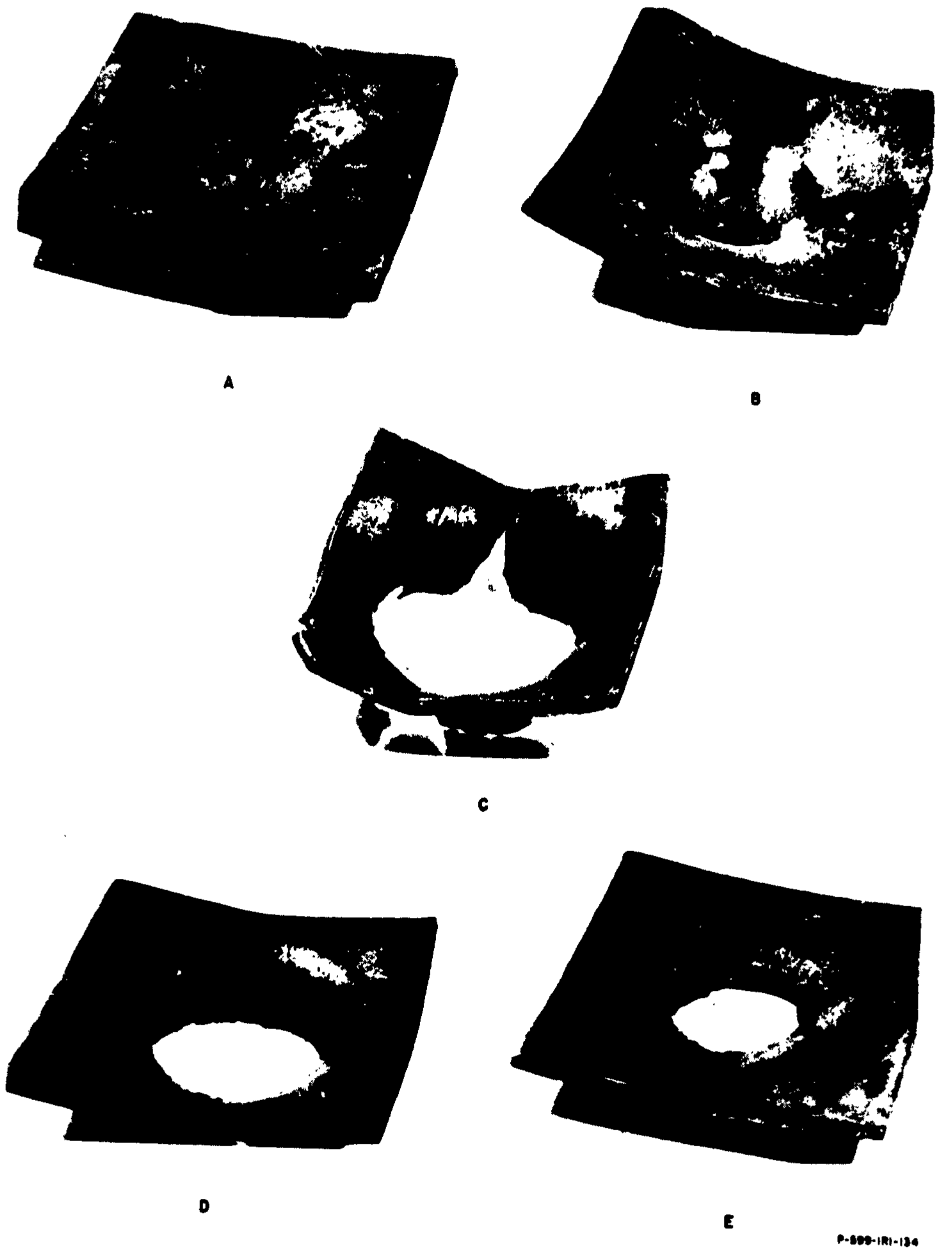

Fig 5 Effect of Variation of Detonation Rate

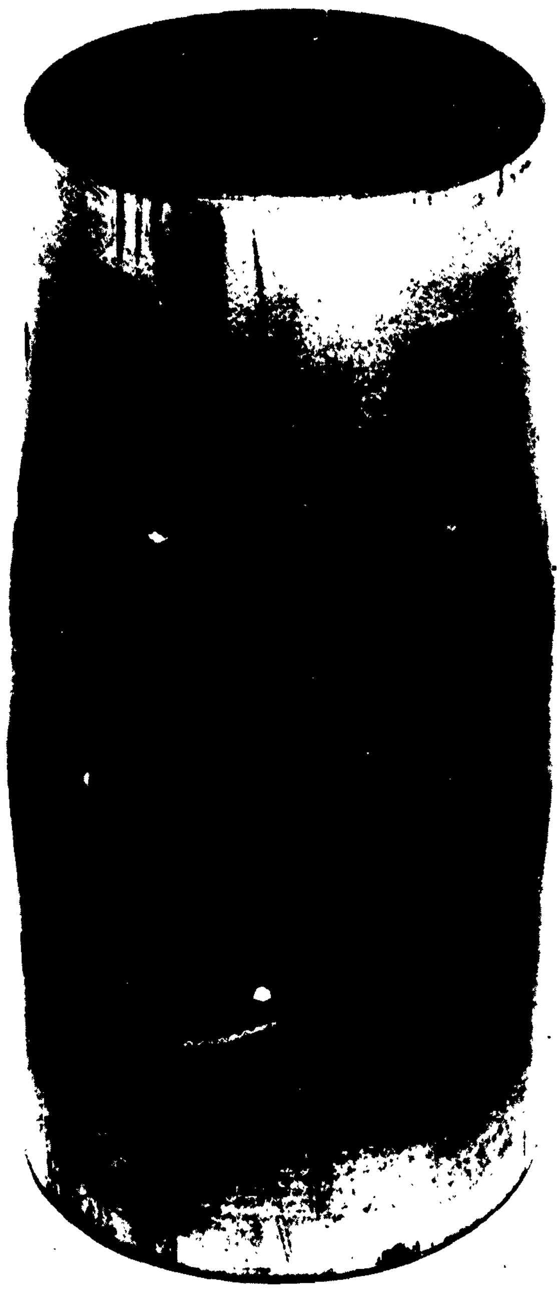

Fig 6 Steel Cylinder after Detonation of ⅛-Inch Sheath of Explosive

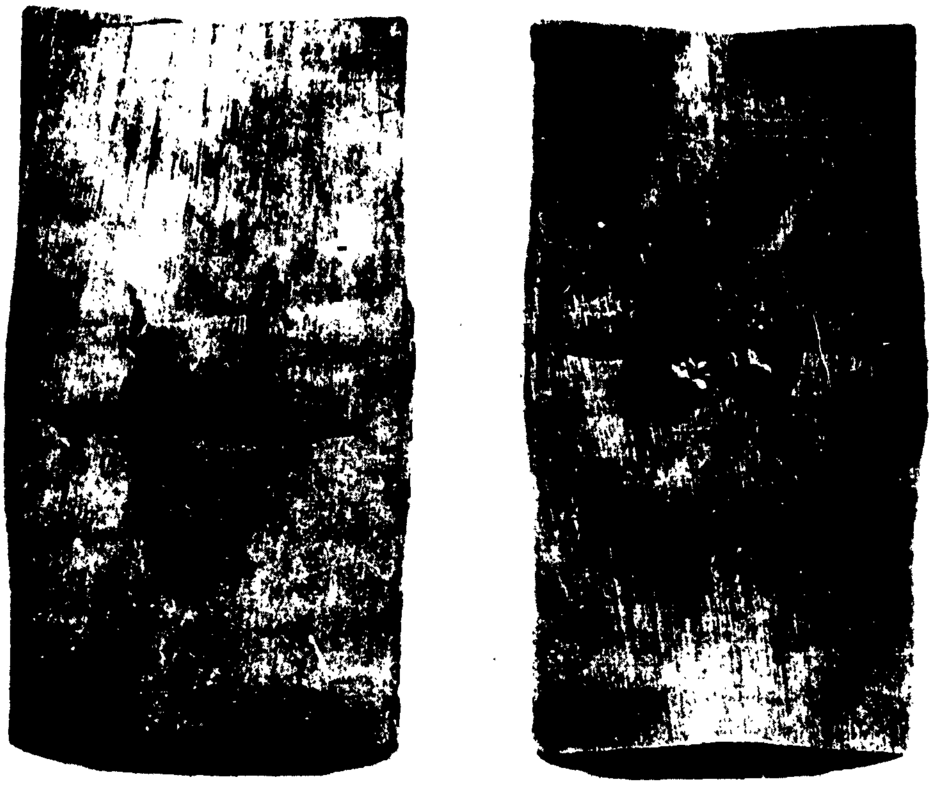

Fig 7   Sectioned Cylinder Showing Cavity and Loose Piece of Steel

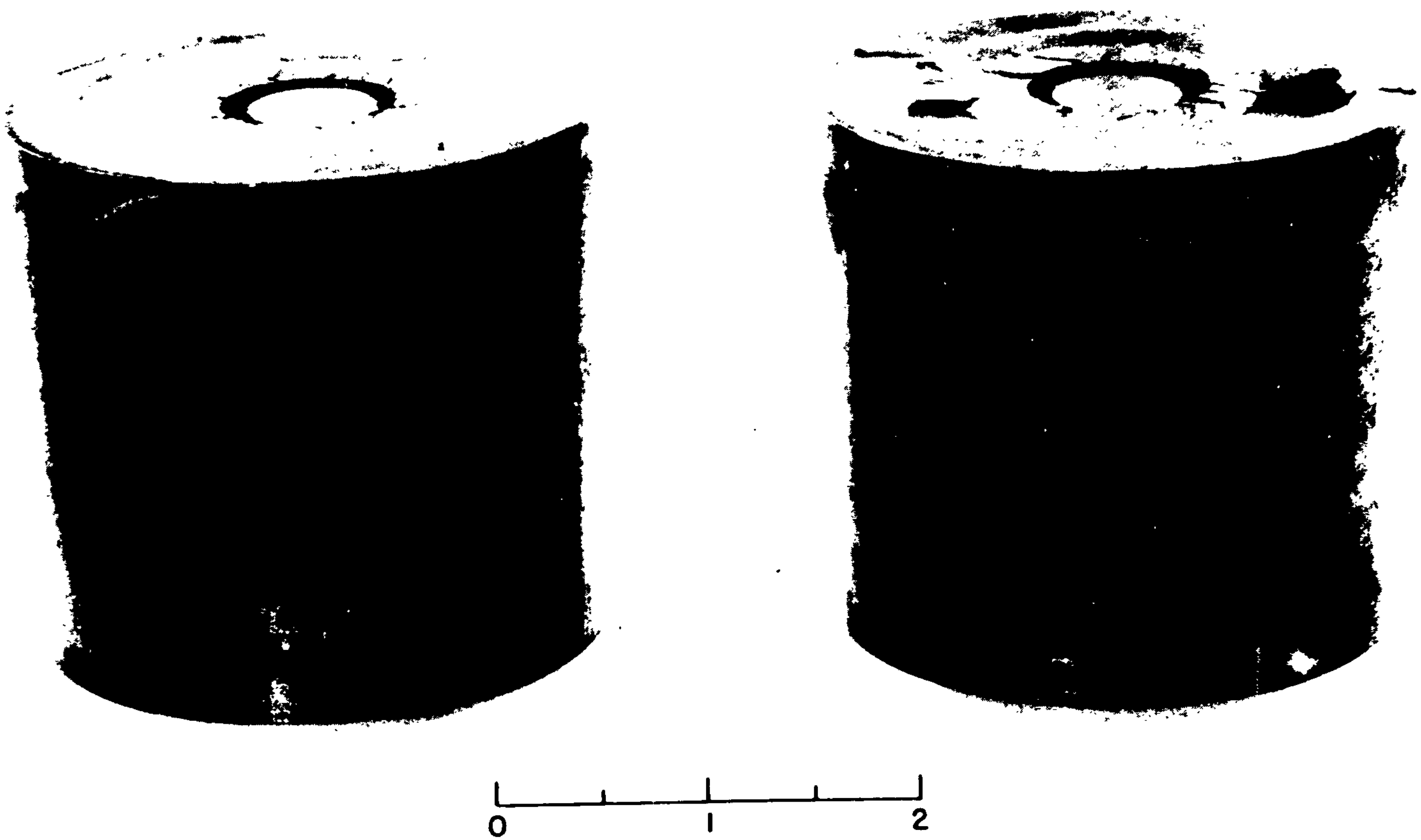

Fig 8 Two Cylinders after Detonation of Sheath of Explosive

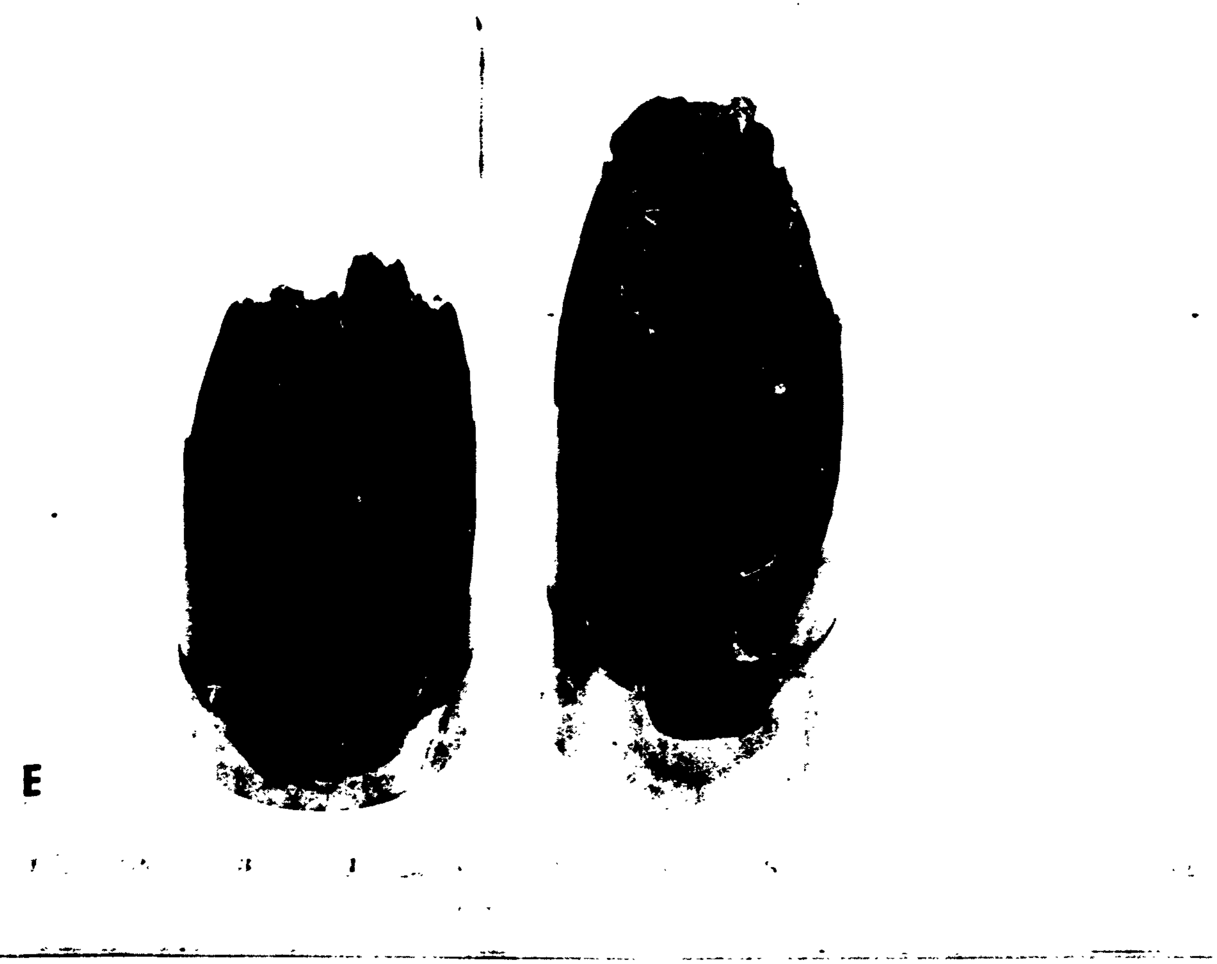

Fig 9 Steel Bar after Detonation of Band of Explosive at Diagonal Points

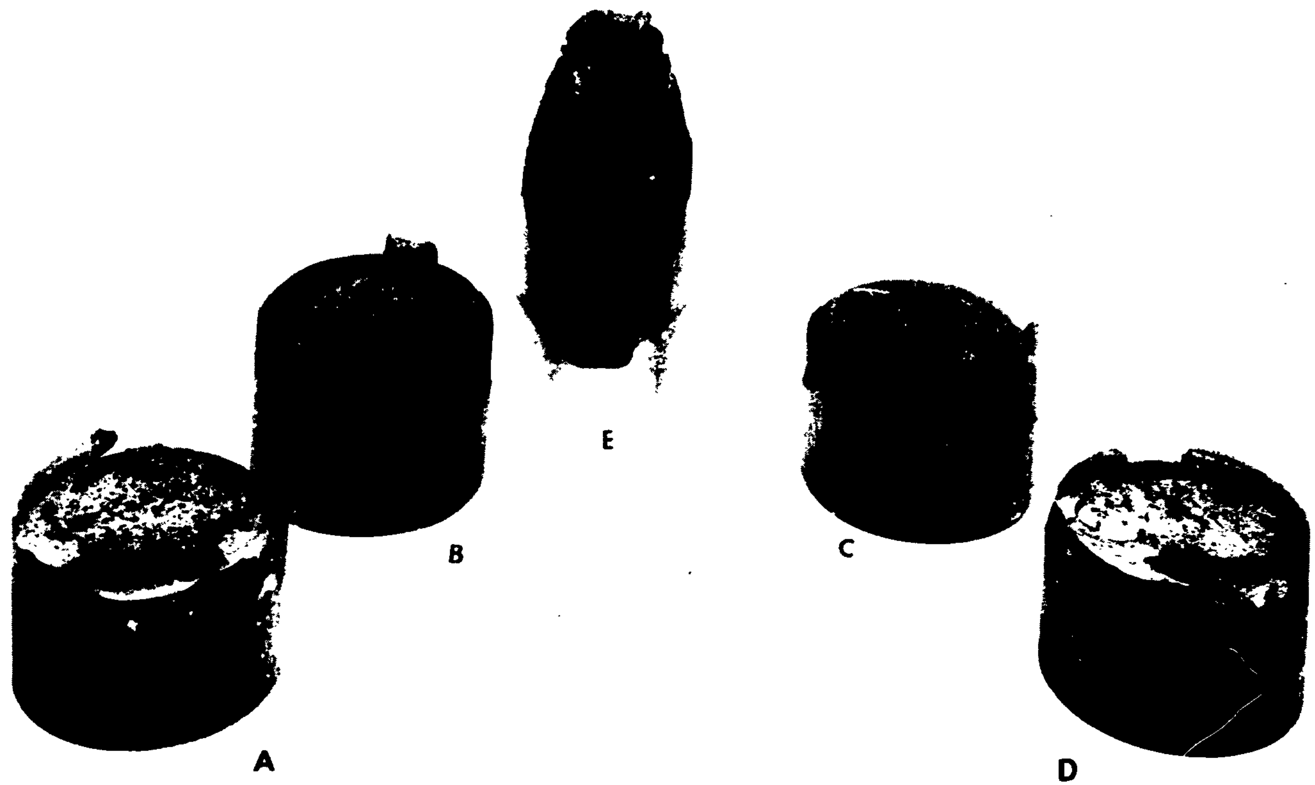

Fig 10 Steel Bars after Detonation of Diamond-Shaped Charges

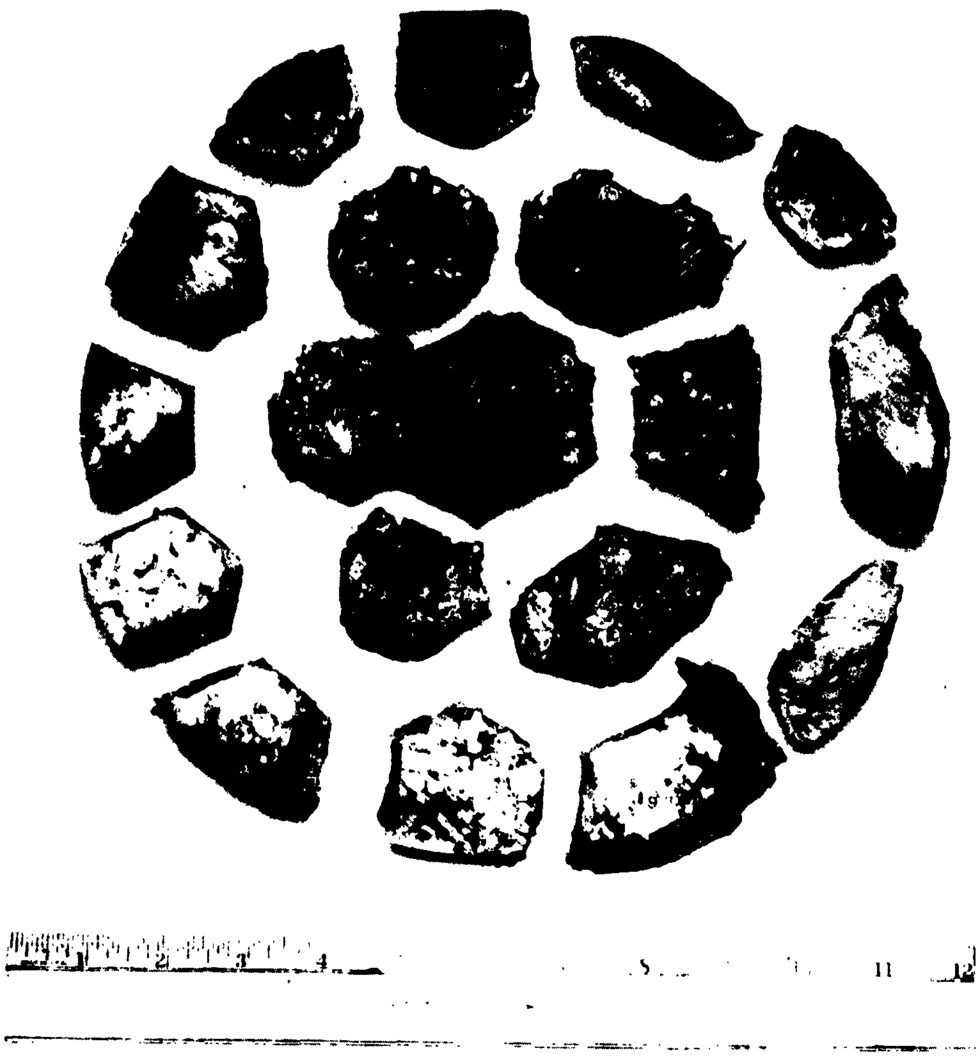

Fig 11   Steel Plate after Detonation of Layer of C-3 Explosive at Nineteen Points

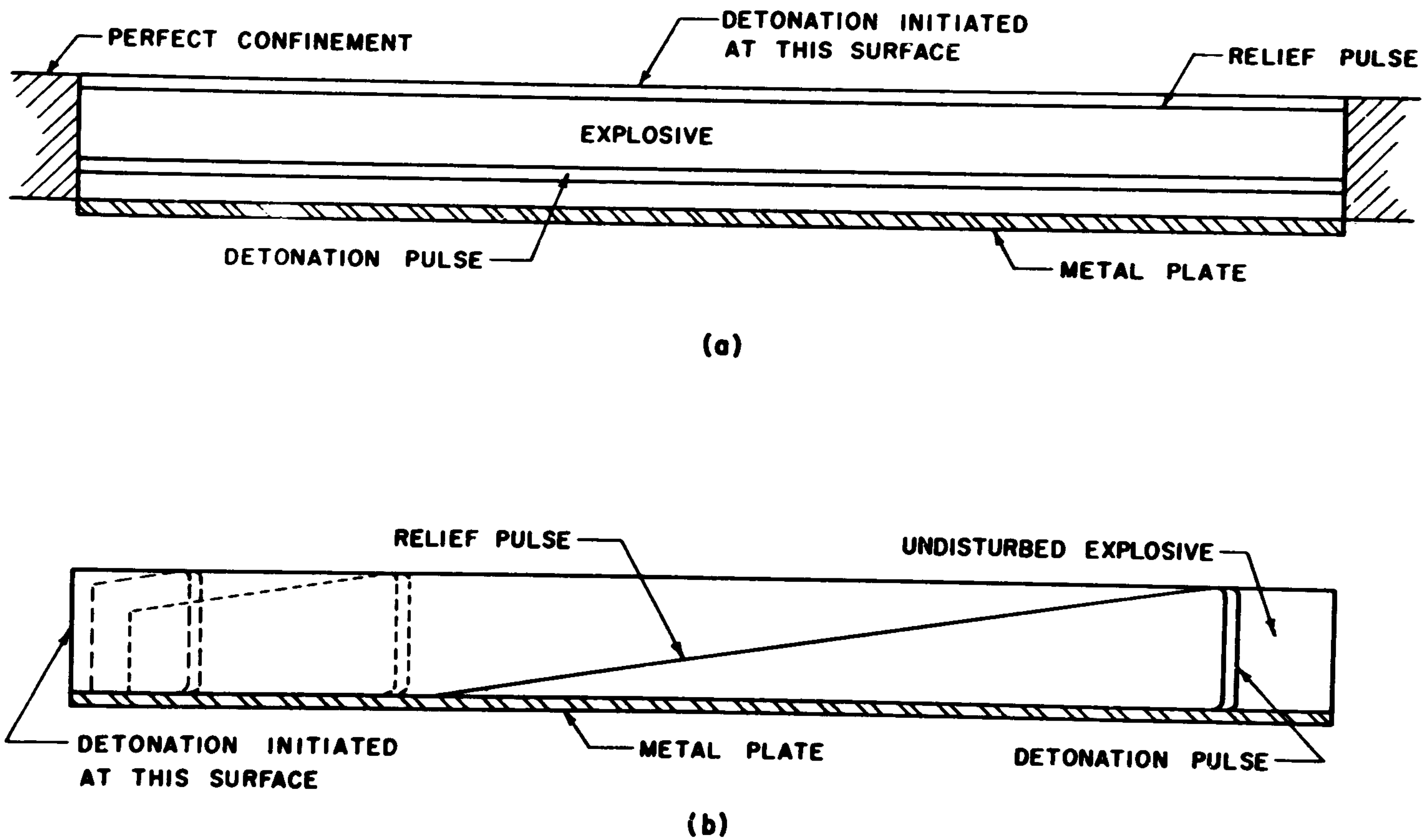

Fig 14 Plate Velocity as a Function of Orientation to Detonation Front

TEST NO. 17 - SPHERICAL LINER 0.062" THICK

Fig 15 Effect of Change in Radius of Curvature on Penetration

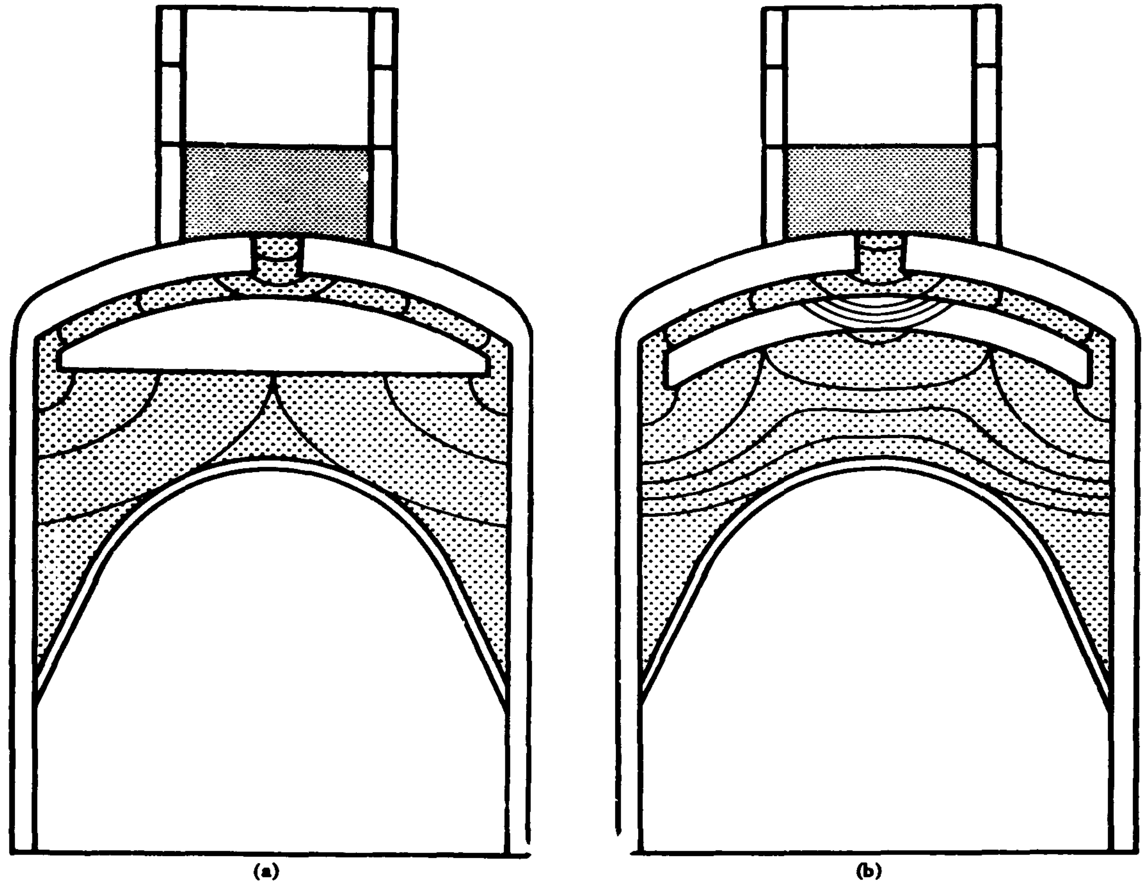

Fig 16 Wave Shaping in Lined Shaped Charges

Fig 17 Record of Triple-Slit System in Smear Camera

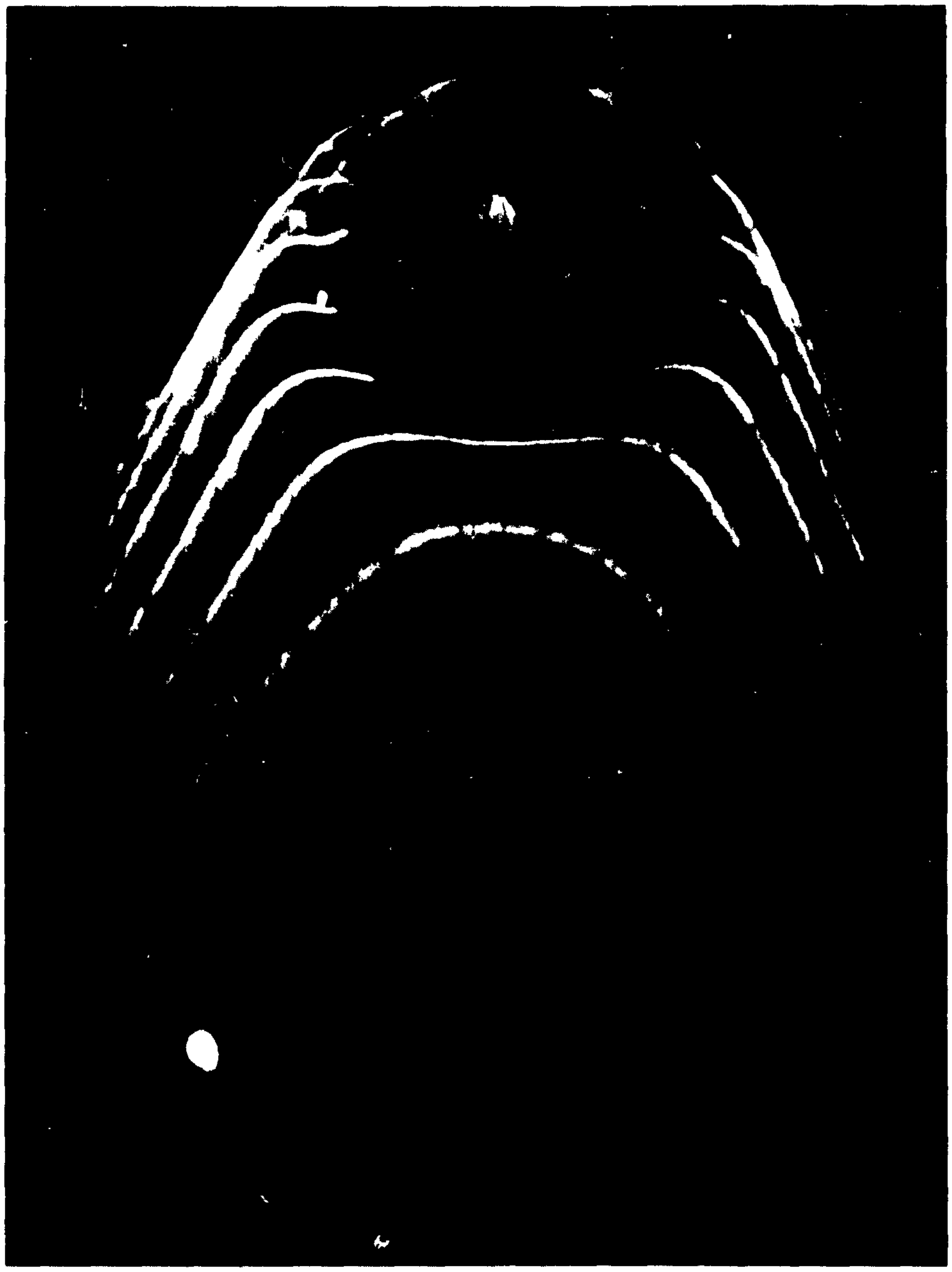

Fig 18 Record of Eleven-Slit System in Smear Camera

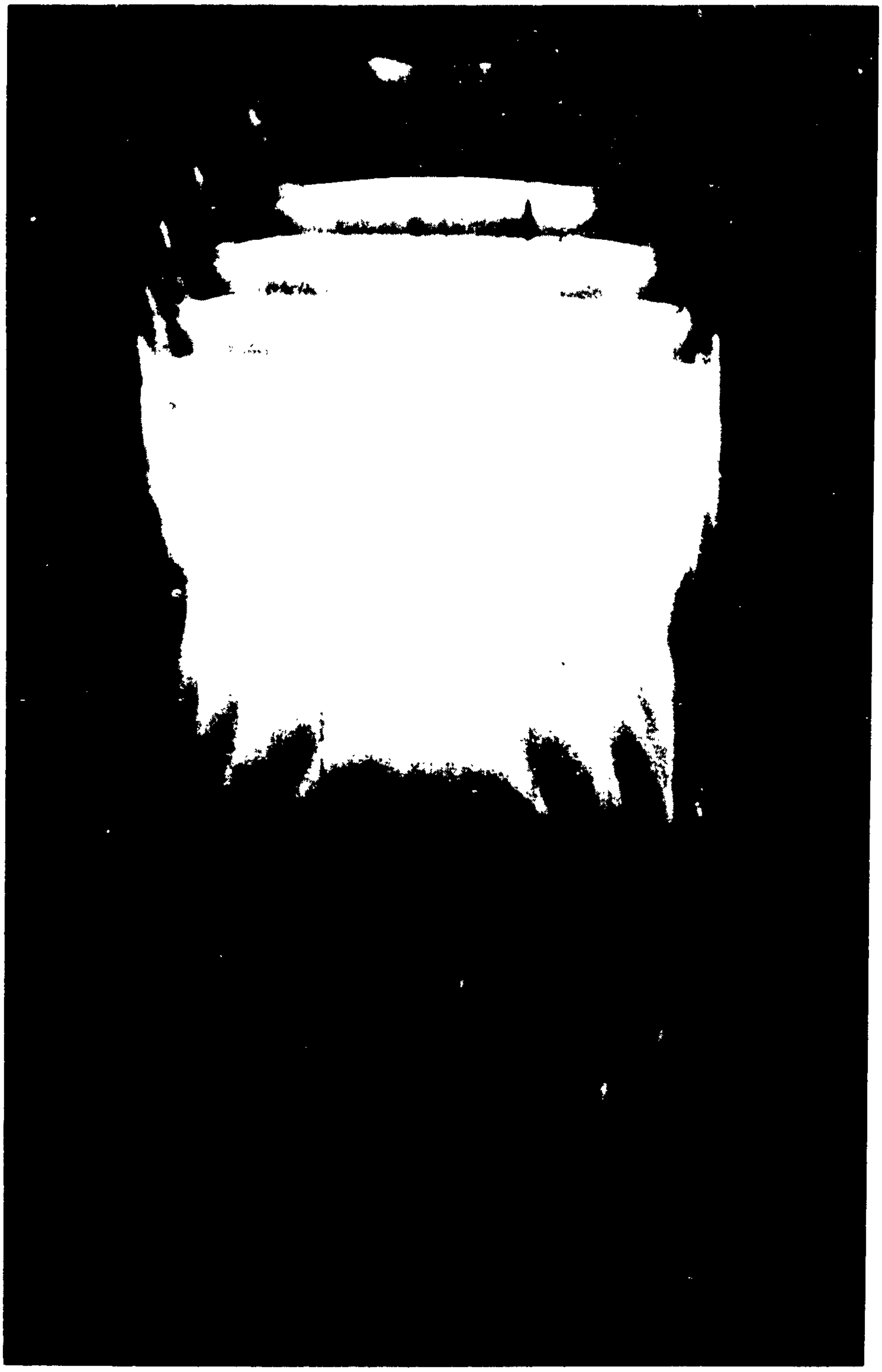

Fig 19 Smear Camera Record Showing "Ghost" Grid of Straight Lines

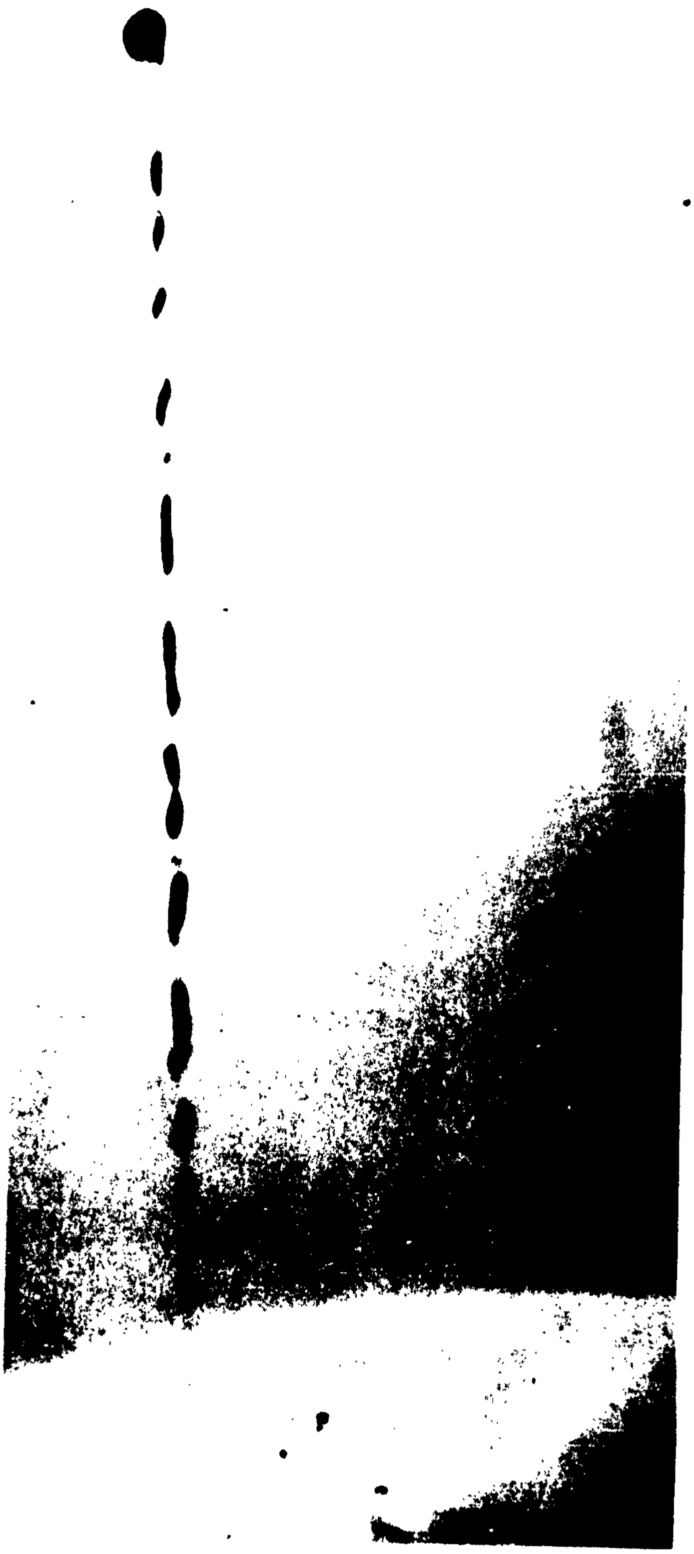

Fig 20 Example of Jet Showing Mass of Metal at Forward Tip

Fig 21 Rings of Fragments Following Jets

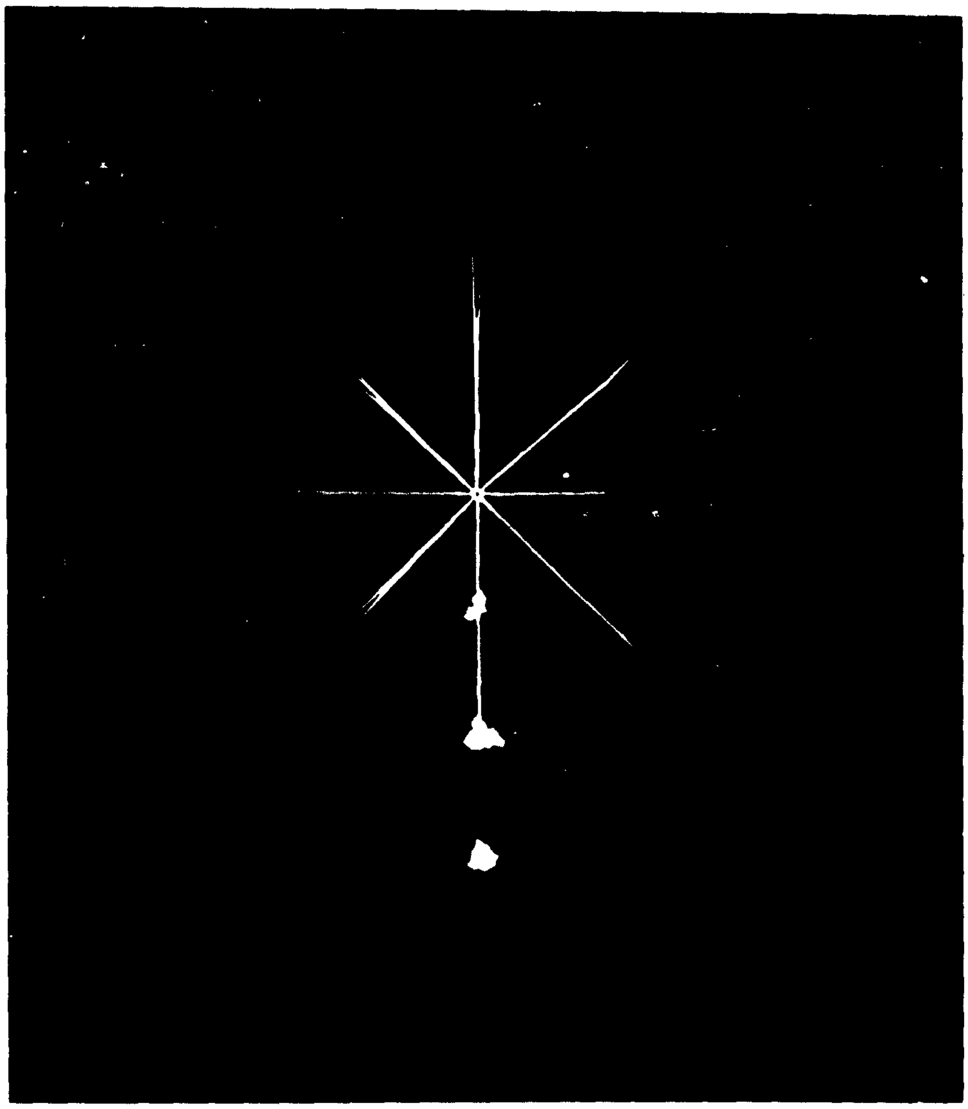

Fig 22 Photograph of Eight-Jet Charge

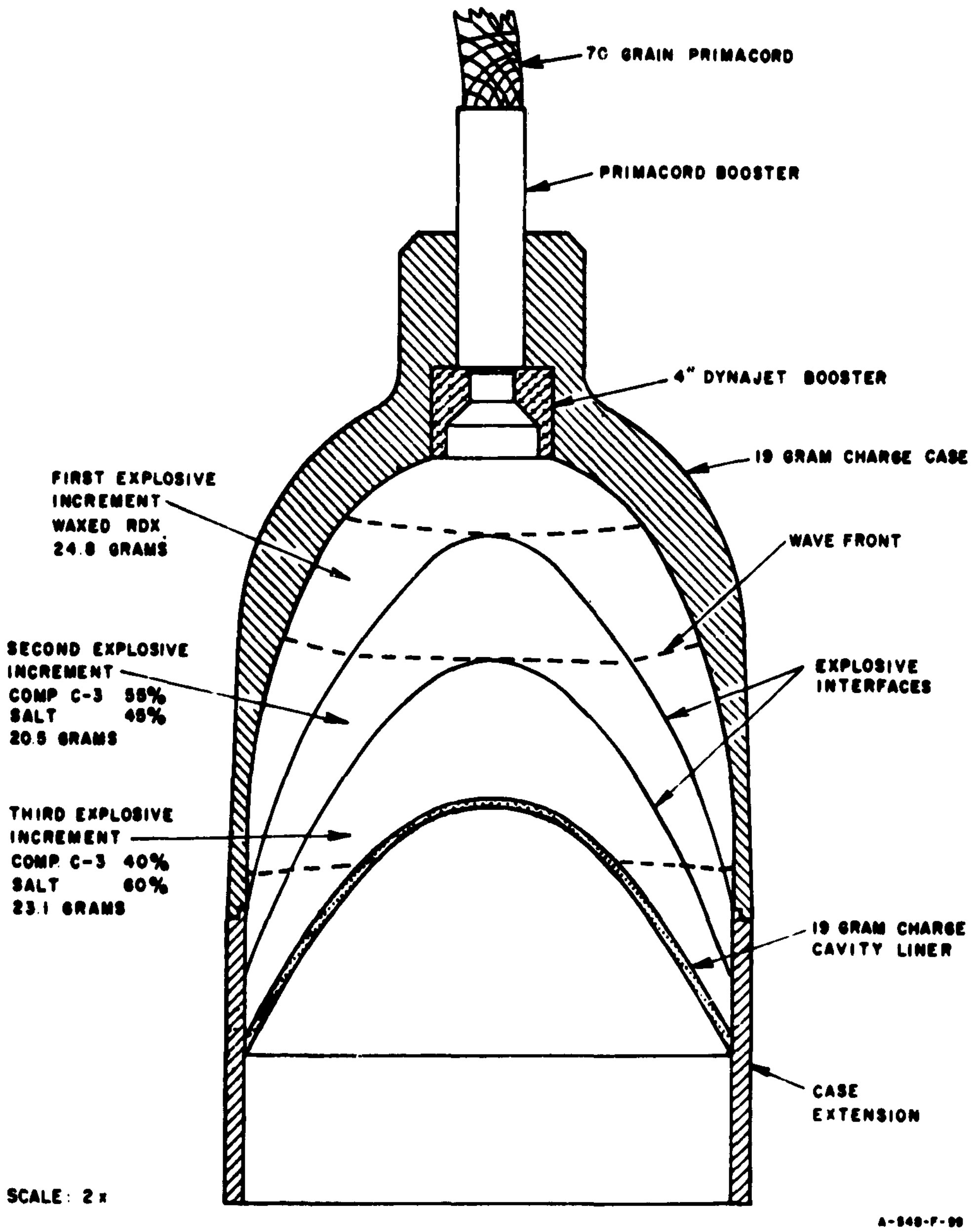

Fig 23 Shaped Charge with Concentric Shells of Explosives

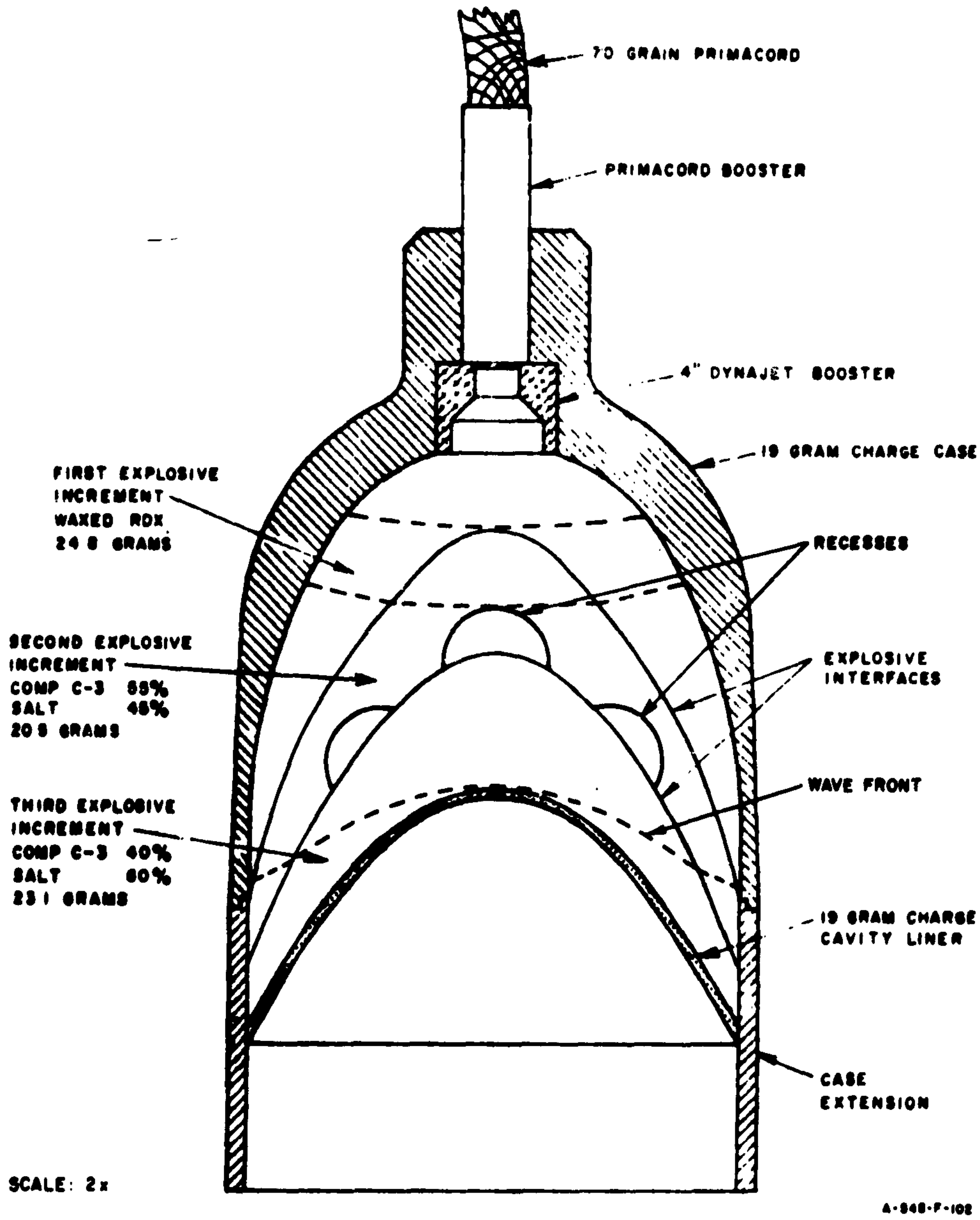

Fig 24 Shaped Charge Containing Unlined Voids (Rece sses)

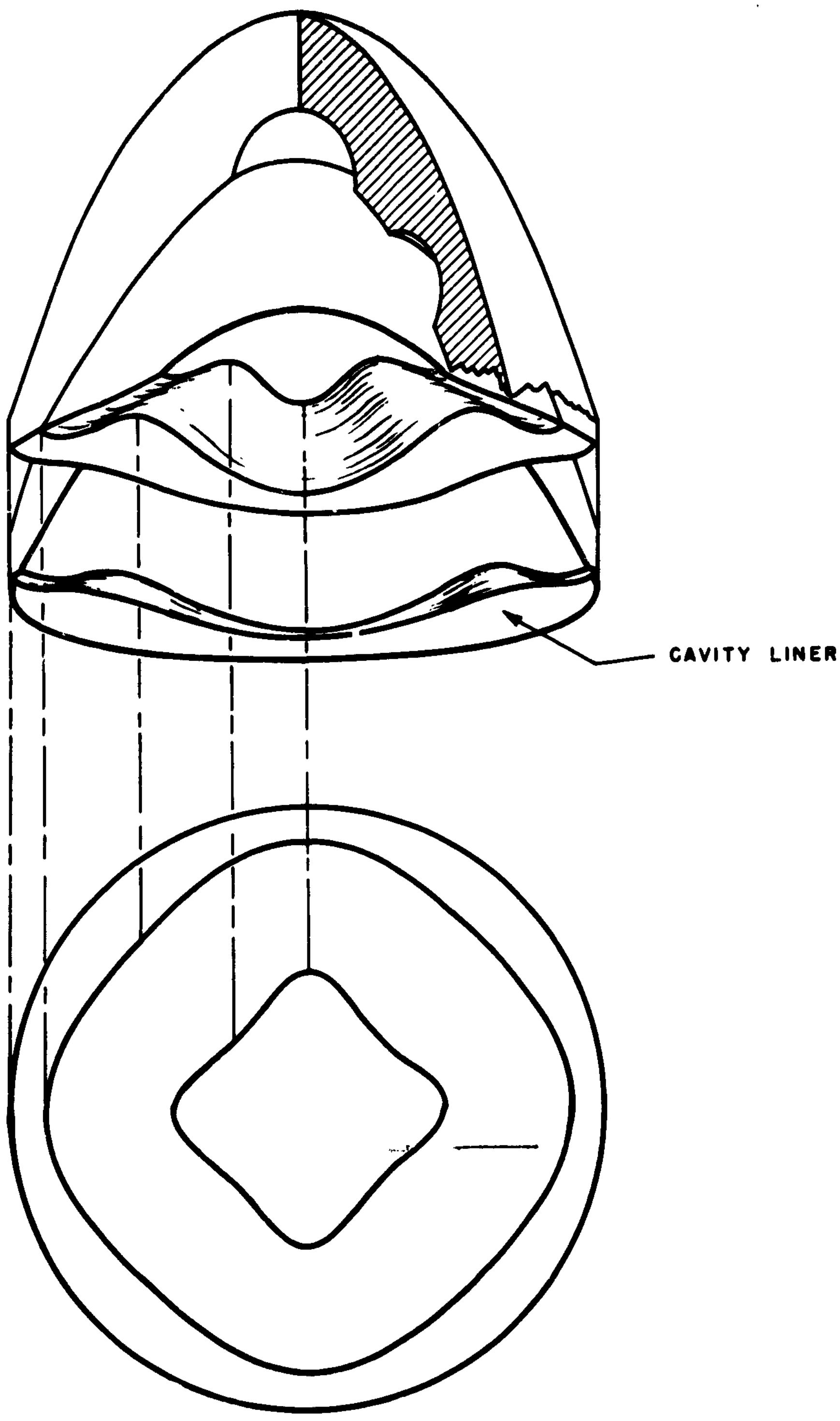

Fig 25 Wavy Detonation Front Produced by Explosive Charge Containing Voids

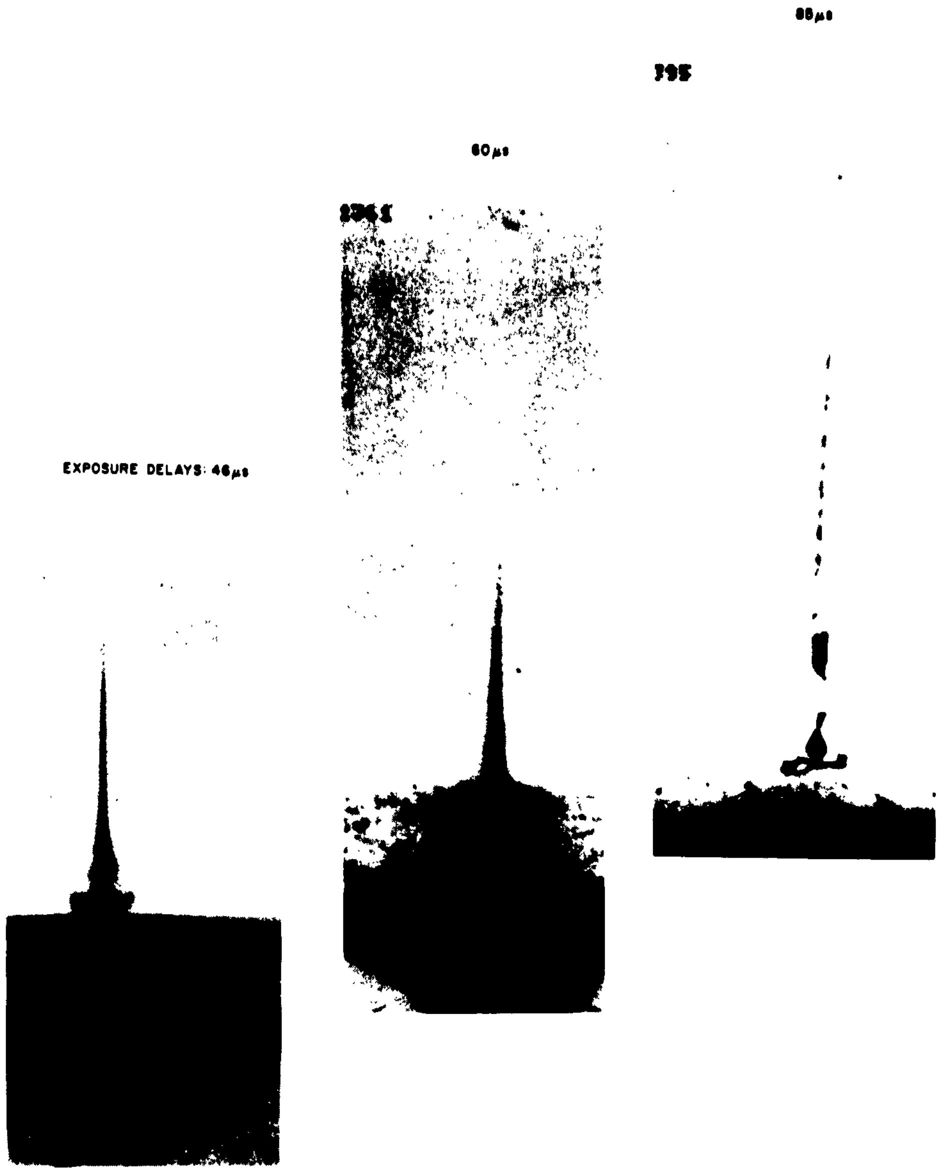

Fig 26 Flash X-ray Picatues Showing Performance of Shaped Charge Containing Concentric Shells of Explosives

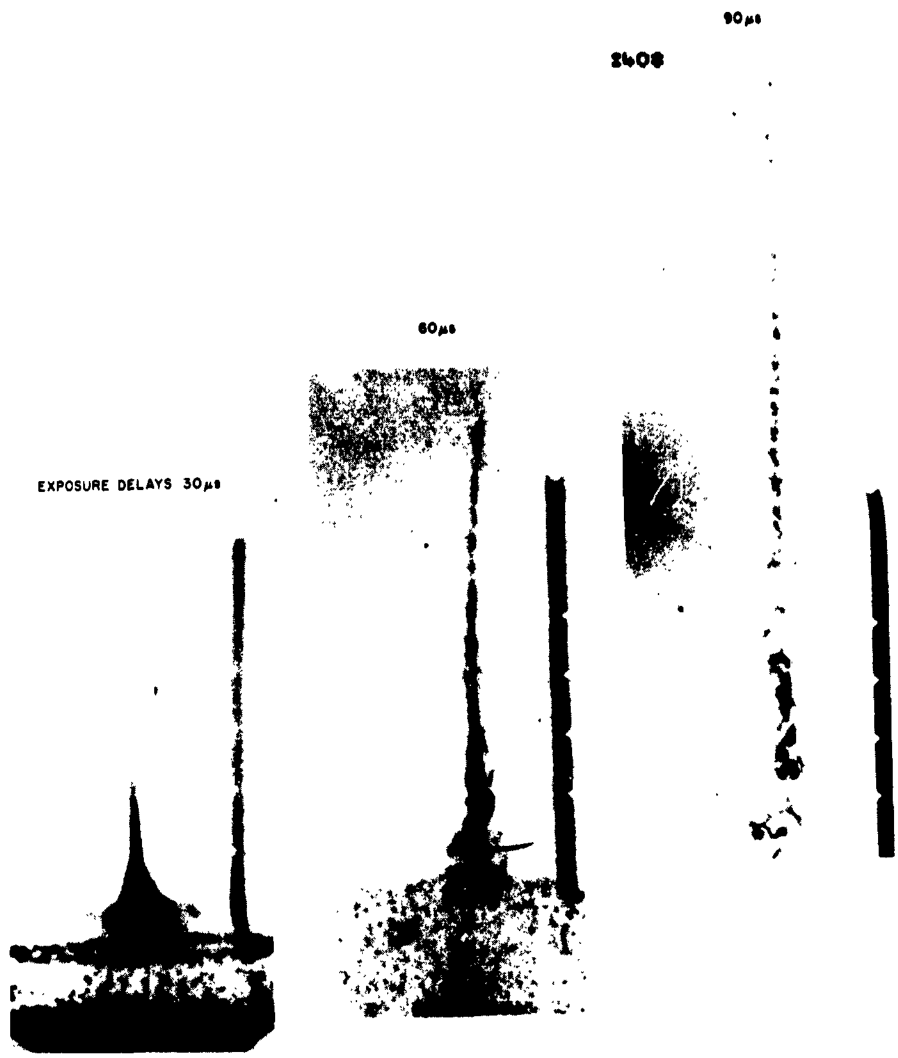

Fig 27 Flash X-ray Pictures Showing Performance of Shaped Charge Containing Concentric Shells of Explosives and Voids

A DYNAMIC RADIOGRAPHIC TECHNIQUE FOR STUDYING EXPLOSIVELY ACCELERATED SYSTEMS

Wilmot Hess

University of California Radiation Laboratory

ABSTRACT

The X-ray beam from a 7-Mev electron linear accelerator has been used to study explosively accelerated systems. The construction and operation of the accelerator are discussed; the radiographic explosive experiments are described; and the system for collecting data presented.

INTRODUCTION

For a number of years, it has been common practice for X-rays of 1 Mev or more to be used for radiographic purposes, for flow analysis, and for similar purposes. As the X-ray energy is increased up to a few Mev, the absorption coefficient decreases, which means that thicker samples can be studied with the same intensity beam. Recently, X-rays from a 22-Mev betatron have been used for radiography.

There are a number of problems in modern science for which the radiographic technique has been applied to the study of dynamic processes. J. C. Clark at Los Alamos has used a 350-Kev X-ray machine to study several high-speed physical processes such as exploding detonators, motion of rifle bullets in the barrel, exploding shells, etc.[1] The technique used here was to take a single short-exposure picture during the experiment to get a stationary view of the system at a certain time.

Dynamic X-ray studies have also been made in connection with some medical problems. Roentgencinematography is a well established technique in which moving pictures are taken of a fluoroscopic screen to study a motion of organs of the human body (particularly the heart). A second less used technique called Kymography[2] is used to study the motion of the walls of the heart. A system of long thin grids is placed behind the patient. A film is placed behind the grid. The film moves

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[1] J. C. Clark, *J. Appl. Phys.* 20, 363, 1949

[2] P. D. White, *Heart Disease*, New York, Macmillan, 1945, pp. 114-115

perpendicular to the long dimension of the slits during the exposure. The motion of the heart walls then shows up as curved lines on the film. This is similar to the optical technique used in smear cameras except that here the film moves, whereas in the smear camera a mirror rotates to spread the picture out on a stationary film.

One general problem that can be attacked by radiography is to study the motions of explosively accelerated systems. Considerable information has been obtained about this problem already. The high-speed photographic technique and the pin technique[1] give information about free surfaces, that is, surfaces that are open to the air and can therefore be observed directly. This type of information is not sufficient in general to completely solve the problem. If the free surface position of an accelerated metal plate is known, this does not necessarily determine the position of the back part of the plate. Several thir. ; can happen that change the static thickness of the plate. The mate^ria: could be compressed; it can flow plastically either parallel or perpendicular to the face of the plate; the plate can break apart or spall; various types o: instabilities can make the free surface rough or can even separate it from the rest of the plate; and jets can give mi leading information about the free surface.

In order to get more information about the motion of explosively accelerated systems, a new technique has been developed. An X-ray beam from a 7-Mev electron linear accelerator has been used for radiographic studies of moving plates. In this way, the front surface and/or the back surface of the plate can be studied. Previously, the back surface could not be investigated. This technique used alone or in conjunction with pin data can give information about back surface velocities, back surface contours, dynamic plate thickness, spall, shock pressure profiles, and undoubtedly other characteristics of explosively accelerated systems.

This report will describe the design and construction of the linear accelerator, the operation and field installation of the machine, the procedure in carrying out an experiment, and the experimental results obtained using this technique.

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[1] Walsh & Christian, *Phys. Rev.* 97 1544 (1955); Minshall, *J. Appl.Phys.* 26463 (1955); Second ONR Symposium on Detonation, Feb 1955, Papers 15, 16 and 17

EXPERIMENTAL PROCEDURE

Firing Table

The 7-Mev electron beam from the linear accelerator strikes a tungsten target which is a range thick for the electrons, and X-rays are produced by the stopping electrons. These X-rays are collimated by a tungsten or heavy-metal collimator which is 60 mils wide, one inch high, and several inches deep. This collimator is placed in front of the target (see Fig 1). The X-ray beam when it emerges from the target has a range of energies from zero to 7-Mev. The peak emission is at about 2 Mev. The beam is predominantly forward and the portion that gets through the collimator is used in performing the experiment. The area of the collimator defines the effective size of the source, which is then nearly a line source 60 mils wide by one inch long. This collimator is built into a blast-wall consisting of several feet of concrete, with a steel face plate for added protection. A cutout in this wall contains a steel insert in which is placed the tungsten collimator for defining the X-ray beam.

The assembly to be exploded and the detector assembly are placed on the firing table outside the blast wall of the bunker. This setup is shown in Figures 2 and 3. A typical assembly to be detonated is shown in Figure 4. A detonator initiates a high explosive lens, producing a plane wave detonation which passes on to the main charge of high explosive. This high explosive accelerates a metal plate placed in front of it across the X-ray beam. The direction of motion of the plate is perpendicular to the direction of the beam. This explosive system is used to produce a flat one-dimensional experiment for ease of interpretation. The detector assembly is placed behind the assembly to be exploded, that is, on the side opposite the assembly from the bunker.

Sodium iodide crystals, which are used as detectors, are built into a linotype metal housing to protect them from stray radiation (see Figs 5, 6, and 7). In front of each crystal is a collimating slit, which also is 60 mils wide by one inch high. Having both the source and the detector well collimated insures that scattered radiation will not reach the detector; hence only the radiation which is transmitted through the assembly being studied will be used.

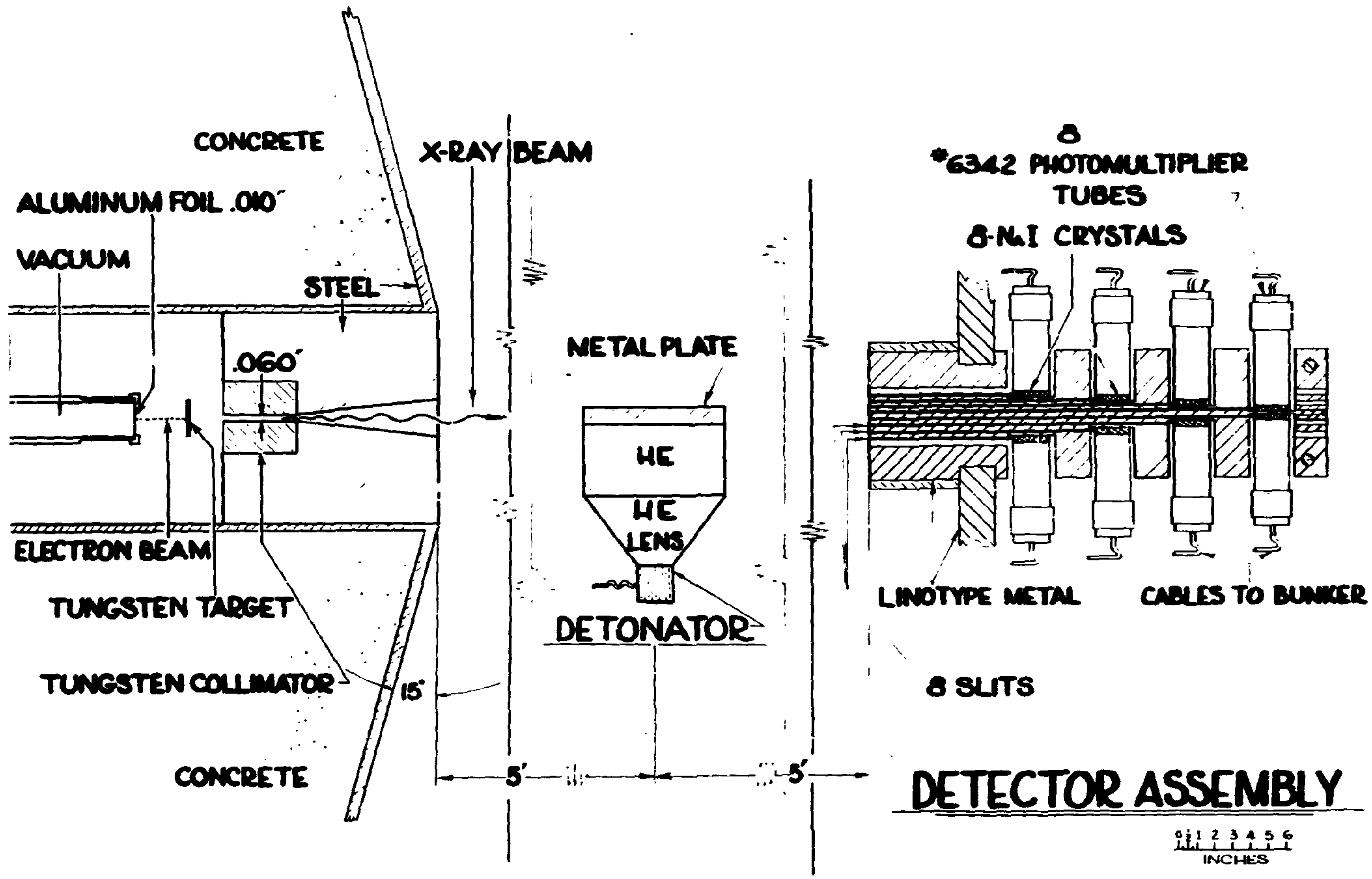

Fig 1 Diagram of Test Setup

The sodium iodide crystals are viewed by photomultiplier tubes. Photomultiplier tube signals are sent back inside the bunker and are photographed from an oscilloscope arrangement. These signals from the X-ray detectors are not signals corresponding to single photons, but are the current resulting from a considerable number of X-ray photons falling on top of each other, such that the current coming from the phototube has a fairly uniform value for something like 10 μsec. In the assembly shown here, eight sodium iodide tubes are built into a linotype metal housing. Hence eight separate pieces of information are obtained about the motion of the plate.

Different geometries of detector arrays have been used. When the experiment is performed, the X-ray beam from the accelerator is turned on, the high explosive is detonated, and the metal plate then moves across the X-ray beam. The strength of the signal received by one of the sodium iodide crystals will depend upon the presence or absence of the metal plate in the line of sight of the beam to this detector from the source. As the metal plate moves across the beam, the signals from the slits will increase after the back surface of the plate has moved out of the X-ray beam. In this way, the position of the back surface of the plate is detected by observing when the signal from the sodium iodide crystals suddenly increases. Calibrated time bases are put on the oscilloscope receiving the sodium iodide pulses; hence the times at which these signals increase can be measured, and in this way the history of the back surface of the metal plate may be studied.

This type of experiment is a shadowgraph study. The surface of the moving metal plate is observed by noting a change in transmitted beam strength when it moves out of the beam. That is, the X-ray shadow of the plate is observed. There is another type of experiment which can be performed with this same apparatus. It might be called a transmission experiment to contrast it to the shadowgraph experiment just described. In the transmission experiment, the assembly to be studied is also placed so that the motion of the assembly is across the beam; however, the variation of intensity of the X-ray beam which is transmitted through a metal plate or through high explosive is followed.

A shock wave moving through either a metal plate or an explosive is

studied. The shock wave produces compression in the material, which increases its absorptivity, and the intensity of the X-ray beam reaching the sodium iodide crystals is decreased. One obtains directly the number of grams per square centimeter of material in the beam and may, by using an equation of state of the material, determine the pressure in the region through which the X-ray beam is being transmitted. From the view of a single detector slit over a period of time one can obtain the pressure as a function of time, that is, the pressure profile of the shock wave moving through either a metal plate or high explosive. This experiment does not depend upon the motion of an interface across the line of sight of the beam; rather, it depends only on the change in the transmitted intensity through a component of the assembly.

Linear Accelerator

The accelerator which we use as a source of the 7-Mev electron beam, which in turn is the source of the X-rays, is one which is constructed along the lines of the linear accelerators built at Stanford (See Fig 10). The main section of the accelerator is a loaded wave guide, loaded in such a manner that the phase velocity of the electric wave moving down the wave guide is slightly less than the velocity of light. The electrons which are injected into the wave guide along with the RF energy can then keep step with the electric wave, and energy is transferred to the electrons; hence, they come out with higher energy than that with which they enter the wave guide section. A 300-KV pulse transformer injects electrons into the wave guide. The RF energy is fed into the wave guide from two 2-megowatt klystrons (See Fig 11). These klystrons and the injector both are used with a 10 μsec-long pulse. The electrons then ride the electric wave down the loaded wave guide, and at the end of the guide the RF energy is dumped into a matched load--such that the reflected RF signal is very small--and the electrons, which are now at the 7-Mev level, go out through a thin vacuum window and strike the tungsten target to produce the X-rays. The two power klystrons are excited by a third driver klystron to make them operate at the same frequency, and the outputs of the two klystrons are phased and attenuated so that they are matched and fed into the wave guide.

Electronic System

Figures 12 and 13 show the data recording and timing and amplifier sections of the electronic system in the bunker. Since the durations of the X-ray beam is about 10 μsec and the total history of an

experiment may take several times this long, timing becomes a serious problem in conducting these experiments.

When an interlock chain has been completed (which assures that all the equipment is functioning correctly, camera shutters opened, and the firing unit activated) the experiment can be started. At this time a button is pushed which allows the next pulse from the repetition rate generator to trigger the firing unit. This pulse does several other things: It turns on several raster sweep timing-scopes with which timing pulse data are collected for tying together different items involved in the history of the experiment, and pin signals (if used) are collected. The pin data are often used to study the front surface of the moving metal plate while the linac is being used to study the back surface of the plate.

The firing unit is of the capacitor discharge type. It sets off the electric detonator used in initiating the high explosive. A pulse out of the capacitor discharge unit is displayed on the timing scope to indicate the start of the experiment. The pulse out of the repetition rate generator also goes through a time delay, which has been set accurately before the experiment, comes back, and turns the linear accelerator on at a certain prescribed time. This pulse out of the delay unit triggers the oscilloscope sweeps which are to record the phototube signals--somewhat earlier than the accelerator beam comes on--so that they will get the complete X-ray pulse history from the accelerator as shown in the functional block diagram (Fig 8).

The pulse out of the delay unit also generates a fiducial pulse which is displayed on both the timing oscilloscope and the signal oscilloscopes. This fiducial pulse provides a known time-from-start-of-experiment mark on the signal oscilloscope sweeps. A Rossi dot sweep circuit is used on these signal oscilloscopes to provide a time calibration for the sweeps. The dots occur every .2 μsec. With this system, the time from the start of the experiment can be read at any place on the signal scope sweeps. The sweep duration of these signal oscilloscopes is about 15 μsec. The linear accelerator beam pulse lasts 10 μsec. Out of the history of the experiment, this 10 μsec period had been chosen before the experiment began, as the most interesting.

With the system described here, the assembly is detonated, the linac turned on at the proper time, and data collected in such a way that the time from the start of the experiment to the time when an interesting

X-ray beam intensity change occurs can be measured accurately.

The overall timing accuracy of the system is from .1 to .2 μsec. This is due to several effects: X-ray beam statistics, NaI response, amplifier response, and others.

Setup for an Experiment

Position accuracy to 5 mils and time accuracy to about .1 μsec can be obtained with the linac. Because of these numbers, it is quite important that the position of the device, with respect to the X-ray beam, be known quite accurately. The alignment procedure for setting the device onto the table and preparing for the experiment is, therefore, fairly exact. The assembly to be fired is placed on a millhead, which is in turn placed on a structure built onto a large concrete block that, when placed on the gravel firing table, can not be easily moved by mistake. The device can then be accurately positioned by moving the millhead in its two degrees of translation, and also in rotation. The linotype metal housing which holds the detectors is placed on a similar concrete block and millhead for accurate adjustment.

Preliminary alignment is accomplished by using a transit placed behind the linotype metal housing. After the transit is accurately lined up looking down the collimator in the bunker wall, the linotype metal housing is placed in the line of sight between the transit and the snout of the collimator. The back of one of the slits in the linotype housing is open to permit an optical line of sight through the assembly; hence, by using the transit, one can look down through the slit in the metal house and observe a light placed inside the bunker and behind the collimator. The system forms a diffraction pattern due to sizes of slits and spacings, such that a quite accurate setting can be made to determine the centering of the assembly with respect to the beam by setting on the maximum of the diffraction pattern of the light from the slit in the detector house.

After this optical alignment has been completed, a final more accurate alignment procedure is gone through which uses the X-ray beam itself rather than an optical setup. In this case the X-ray beam is turned on, and several parameters are varied to make sure the system is working correctly. First, the detector house is located with the assembly to be

fired not yet in position. The detector house is rotated and translated to see that the detectors are getting maximum signals. Then the assembly to be fired is placed on its stand on the firing table and is located in the proper position for the experiment. The device is moved perpendicular to the X-ray beam, and every few mils a reading is taken of the signal strengths received by all eight detector slits. In this way, the response of the detector system to a known number of grams per square centimeter of material in the line of the beam is obtained.

The slit closure curve obtained from the measurements is shown in Figure 9 for a semi-infinite slab of material; that is, an essentially infinitely thick slab with a flat face parallel to the beam and moving into the beam. The slit closes in about 40 mils of motion of the beam. A theoretical curve has been superimposed on the experimental points to show that the system does behave as predicted. If the linotype metal housings are not carefully constructed, it is found fairly frequently that some cross talk occurs; that is, that one slit will start receiving information when its neighbor slit is open. If the assemblies are well manufactured, this does not happen, and the detectors are essentially independent and behave as shown in Figure 9.

In some instances the piece of metal to be studied may not have a flat back surface. Because of this the data for the resolution curve, as shown here, are taken very accurately in these cases. It is normally the case, when motion other than the very early motion of a metal piece is to be studied, that the back end be tapered in such a way that two-dimensionality will not interfere with the collection of data. That is, the back surface of the metal plate is shaped in such a way that the central region of the plate will be farthest back during the time the experiment is performed. In this way the X-ray beam will detect this central portion of the plate which is the portion most representative of the experiment. Interpretation of the experiments requires the use of the static resolution curve taken before the experiment, which gives the signal intensity as a function of the position of the device. When used in conjunction with the oscilloscope traces from the experiment, this static resolution curve enables one to plot the time-position history for the back surface of the plate and, in some instances, to say something about the shape of the back surfaces. When this curve is used in conjunction with the pin data, one may determine the thickness and other characteristics of the plate.

Characteristics of the X-Ray Beam

As mentioned earlier, the X-ray beam has a spectrum of energies from zero to seven Mev, with maximum emission at about two Mev. The mean energy of this beam was measured by taking absorption curves and comparing the gross absorption curve with absorption coefficients known from mono-energetic beams. In this way it is determined that the mean energy is about two Mev. Absorption curves have been taken for several different materials. They prove to have very nearly the same mass absorption coefficient. About 20 grams per square centimeter of any material is required for a mean free path. In this energy range the absoprtion coefficient is very nearly independent of material, or of Z.

With about 30 milliamperes of 7-Mev electrons hitting the target, something of the order of 10^{11} useful X-rays are produced per 10 μsec. Of this number only some thirty or forty thousand are received by any one X-ray detector if there is no absorber in the line of sight from the source. This is essentially due to the very small solid angle of the detector as seen at the source. The fact that this number is fairly small means that there is a statistical problem which is a limiting factor in the accuracy of the experiments. Typical statistical variation of the pulse size of a beam might be 5% from time to time during a single beam pulse or from one beam pulse to another. This then is one of the limits in the accuracy of determining the time at which the X-ray signal has reached a certain fraction of its maximum strength. If a very large piece of material is placed in the beam so that essentially no gammas are transmitted through it, only two or three gamma pulses per 10 μsec beam pulse are detected by any one sodium iodide X-ray detector. This gives a signal-to-noise ratio for no absorber in the beam of something like 10,000 to 1.

The system is also limited by the amount of material that can be placed in the beam and still yield reasonably small statistical variations for accurate measurements of changes in intensity. If more than a few mean free paths of material are placed in the beam, the statistical variation of the beam height becomes large enough to cause serious errors in the measurement of beam intensity. As many as five mean free paths are usually not considered to make this type of work impossible.

RESULTS

Information has been obtained by the method outlined of the motion of the back surface of explosively accelerated plates. The next figure (Fig 14) shows a series of oscilloscope traces for the several detectors in one experiment. They are located in order--Monitor, 1, 2, 3, 4, 5--and it is seen that from the time at which the signal increases on one oscilloscope trace to the time at which the signal increases on the next trace is about nine dots, which at .2 μsec per dot corresponds to 1.8 μsec. The distance from slit center to slit center is 80 mils, or about 2 mm, so that the velocity of the plate in this case turns out to be about 1.1 mm/μsec. If several experiments are performed on assemblies of the same geometry, at different times in the history of the experiment, a quite complete velocity-time or position-time curve can be built up for the back surface of the moving plate.

Some information has been obtained using the transmission type experiment discussed earlier. In this case, the information pertains to the transmission of the shock wave through the assembly being studied rather than the motion of the parts of the assembly. The next figure (Fig 15) shows the results of such an experiment. There are two superimposed linac traces: the firing trace, the one during which the explosive was fired, is superimposed on the trace immediately preceding. About a third of the way across the trace, one detects the change in signal strength which is a result of the transmission of the shock through (in this case) a carbon block one inch thick by eight inches wide in the direction of the beam. The change in density which is indicated from the change in transmission of the beam here is from a nominal density of 1.6 to 1.9 grams per cubic centimeter.

EXPERIMENTAL PROGRAMS UNDERWAY OR PROPOSED WITH A LINAC

Several experiments have been started using the linac technique:

1. The particle velocity of metals accelerated by explosives can be measured by the linac. This is done by measuring the back surface velocity of accelerated metal plates by the shadowgraph technique. Theoretically the front surface velocity is related to the particle velocity by a factor of two for the same pressure. The work of

Shreffler and Deal[1] gives information about the front surface velocity, but there are several points that cause one to wonder whether the factor of two relating the front surface velocity and the particle velocity always holds true. For instance, the shock reverberation times in the metal plate do not seem to be simply related to shock velocities as they should be; also, the values of front surface velocity do not seem to change with the thickness of the metal plate in a reasonable way. We can test the factor-of-two rule by measuring the particle velocity with the linac and the free surface velocity by pins. Also, the fine structure of the particle velocity may be obtained with the linac.

2. Information can be obtained concerning waves moving through material by performing transmission experiments with the linac, similar to the one described already. A program for determining pressure profiles by this technique has been started. In order to obtain the pressure profile from this type of experiment, the equation of state of the material must also be known.

3. The shadowgraph technique will be used to try to study spall. If a plate spalls and separates, the break between the two parts should result in increased beam transmission. In this type of experiment, it is important that the system be one-dimensional. If the break between the plates is curved, not straight and parallel to the beam, the effect may be obscured. One preliminary experiment of this type showed qualitatively the effect expected.

[1] Shreffler and Deal, *J. Appl. Phys. 24* 44 (1953)

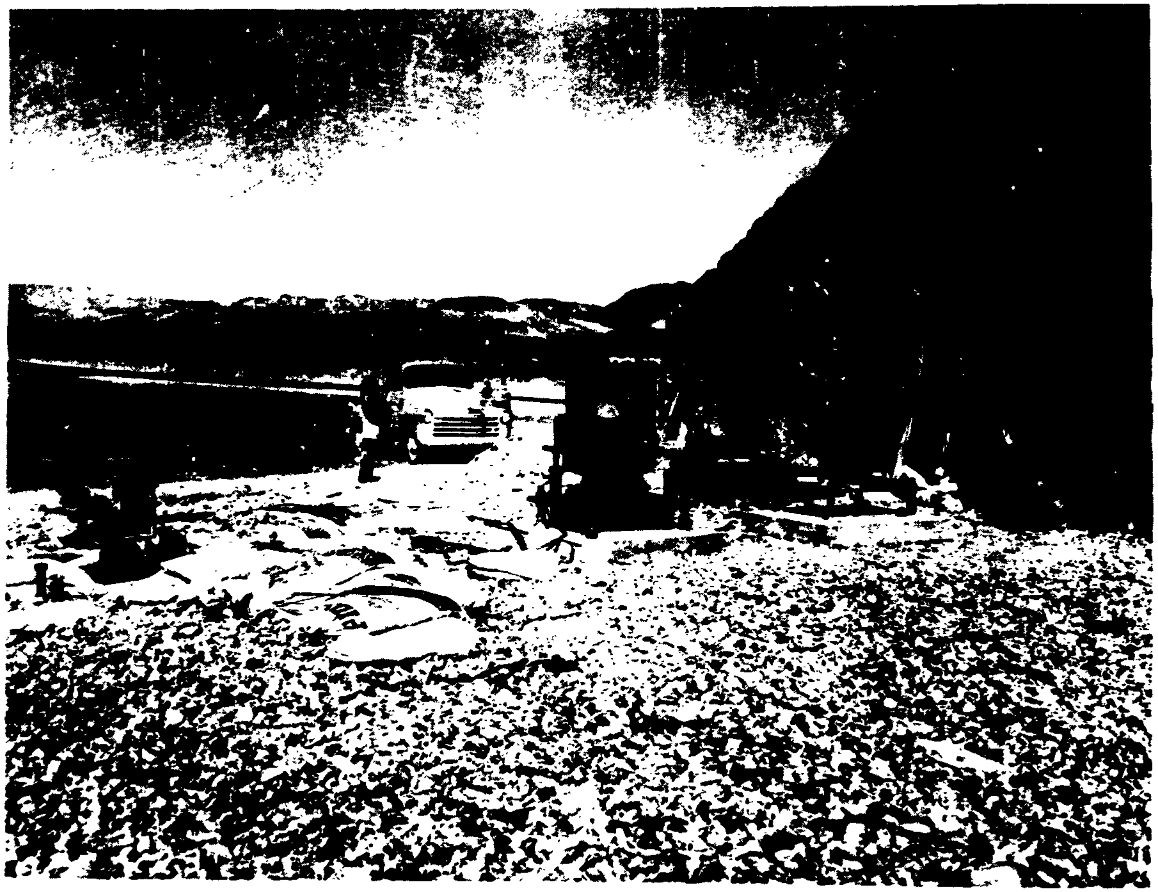

Fig 2 Setup Outside Blast Wall

Fig 3 Close-up of Part of Setup Outside Blast Wall

Fig 4 · Typical Detonation Assembly

Fig 5 Housing for Sodium Iodide Crystals

Fig 6 Housing for Sodium Iodide Crystals

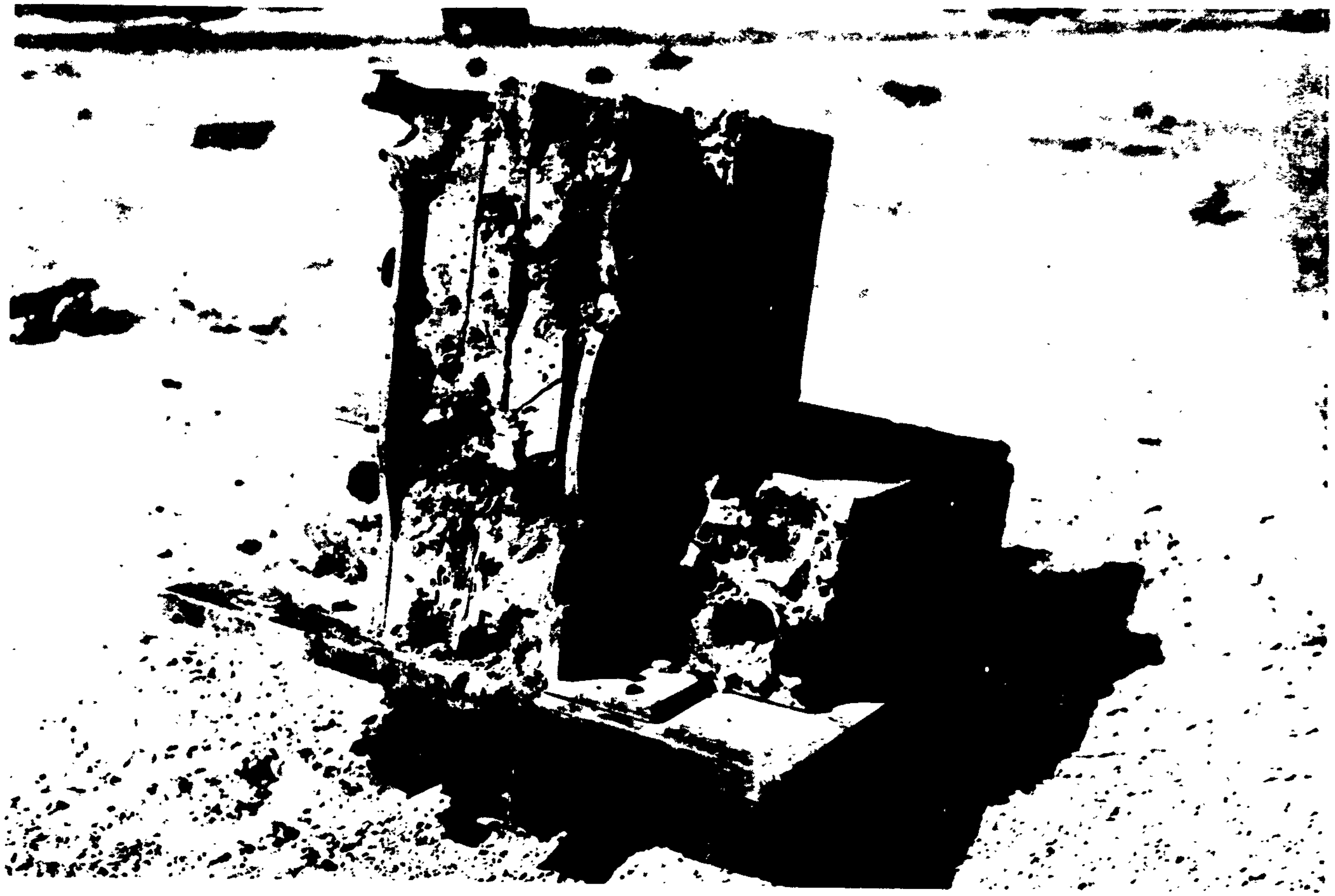

Fig 7 Housing for Sodium Iodide Crystals after Detonation

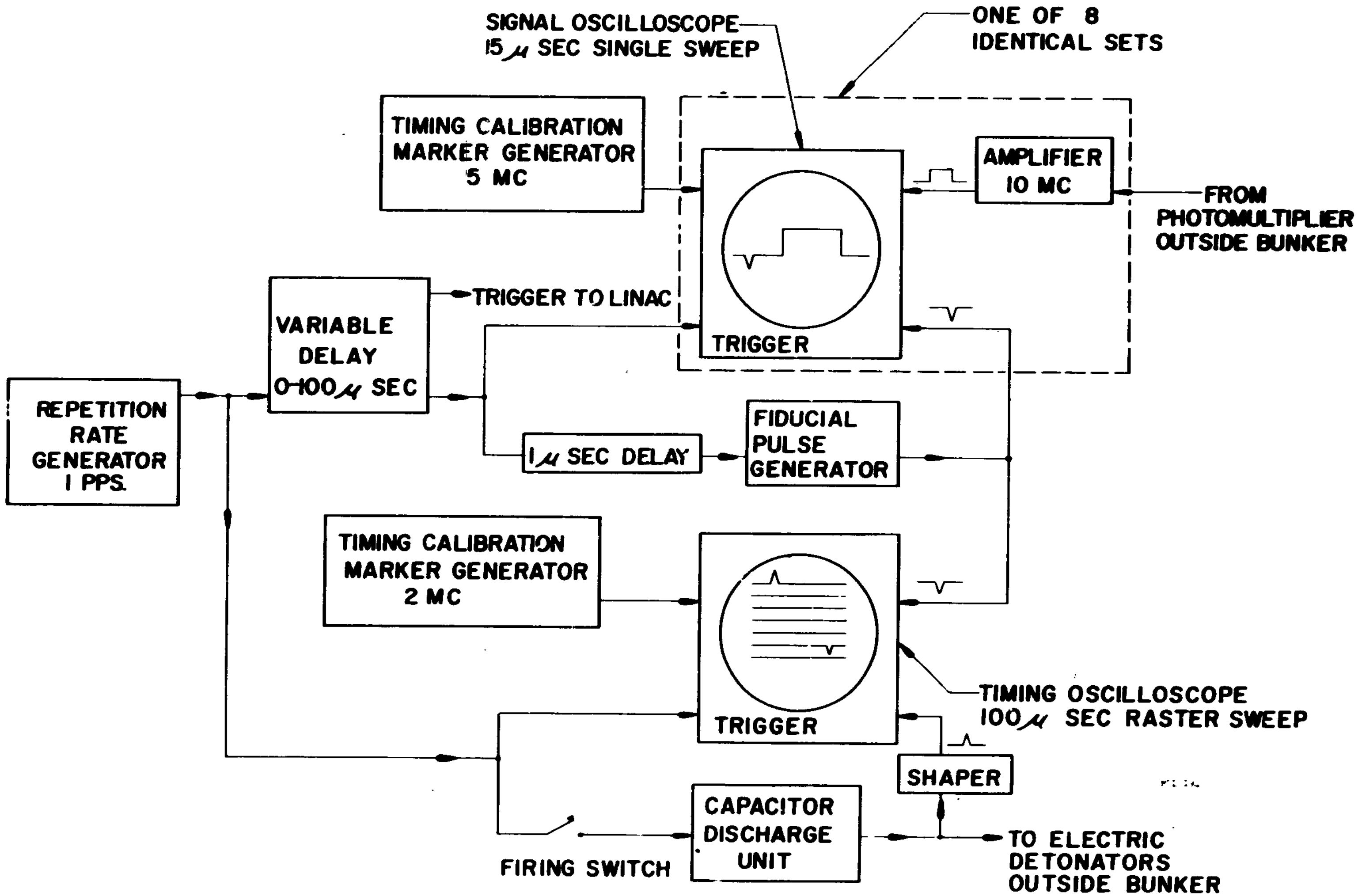

Fig 8 Diagram of Electronic System

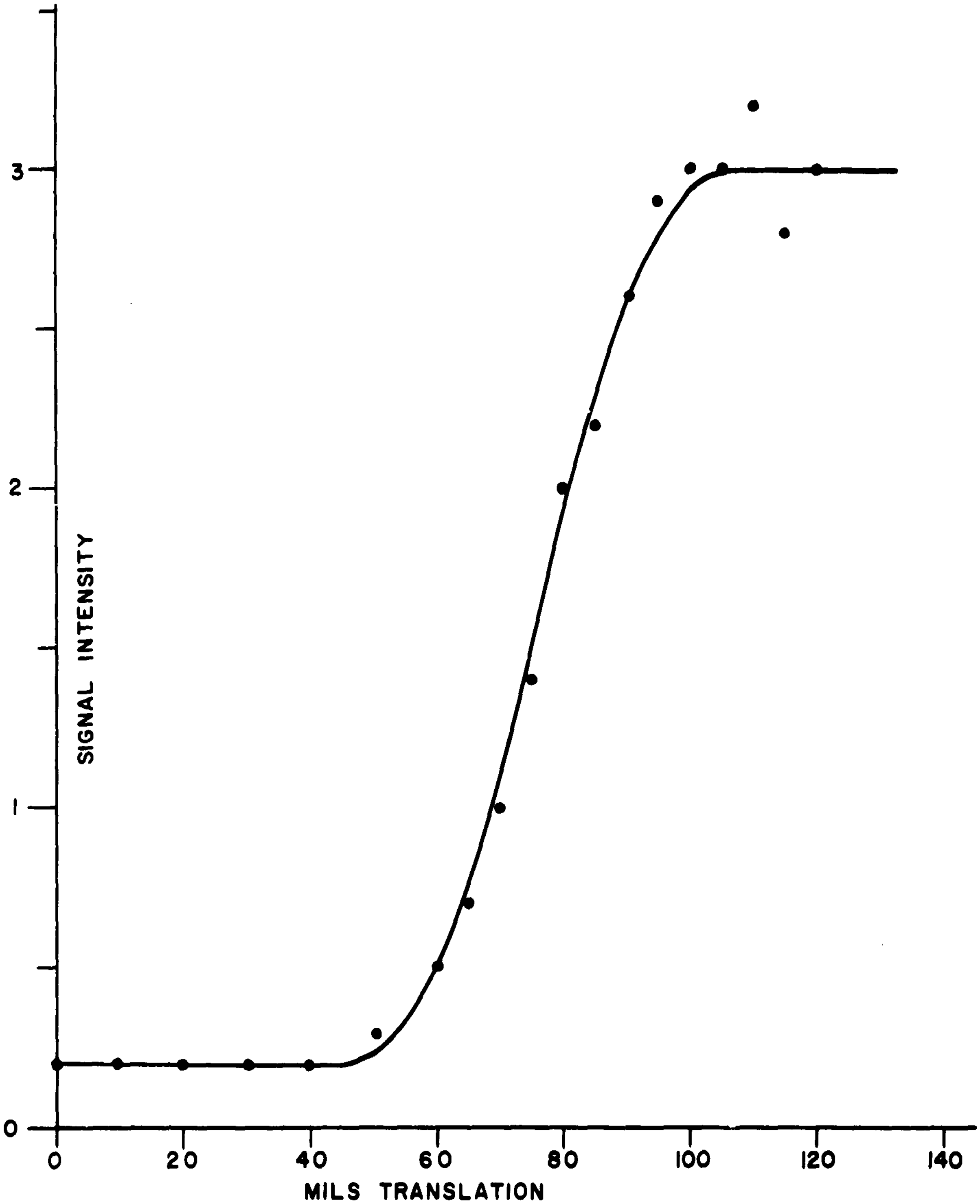

Fig 9 Slit-Closure Curve for a Semi-Infinite Slab of Material

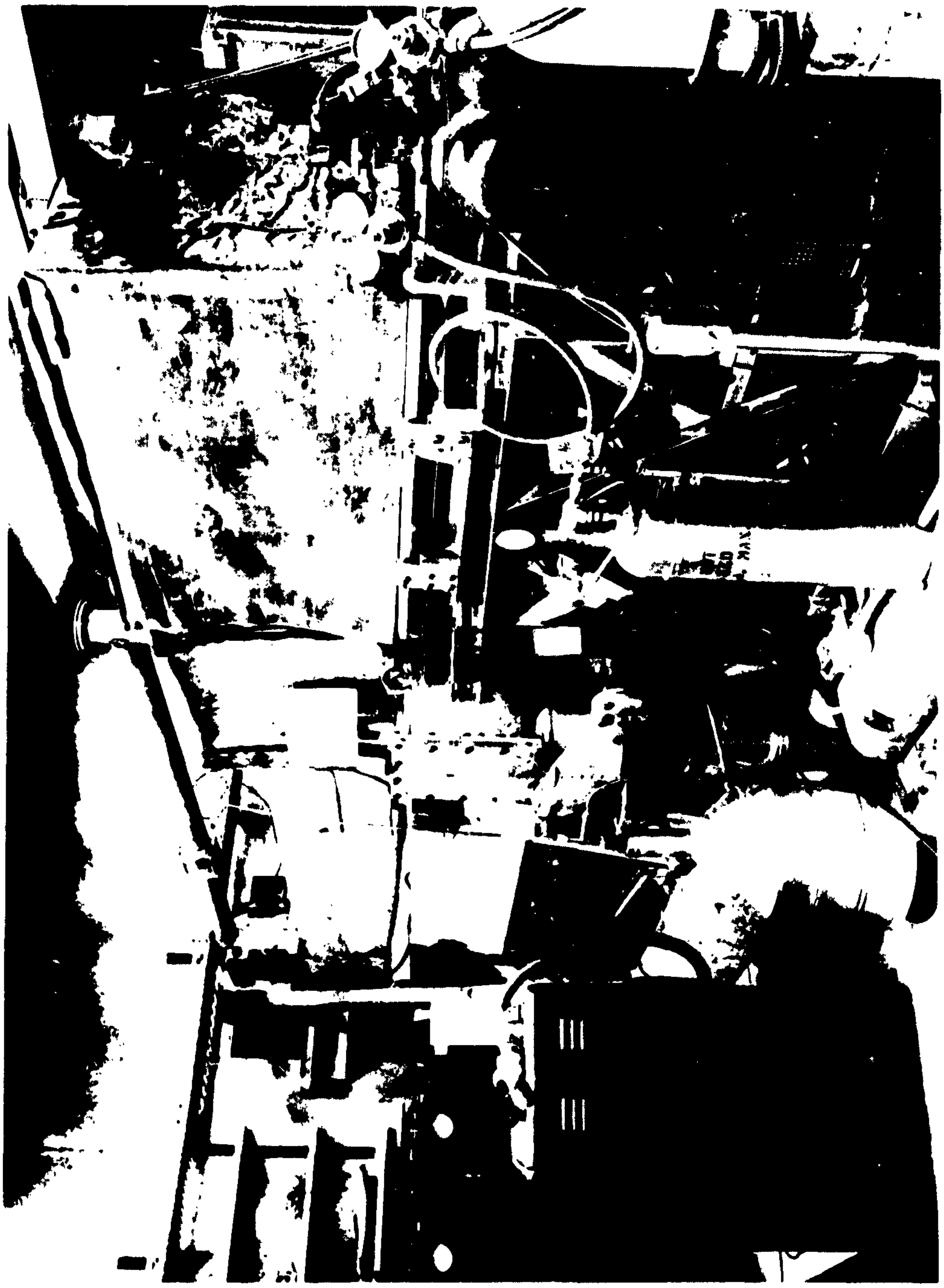

Fig 10 Linear Accelerator

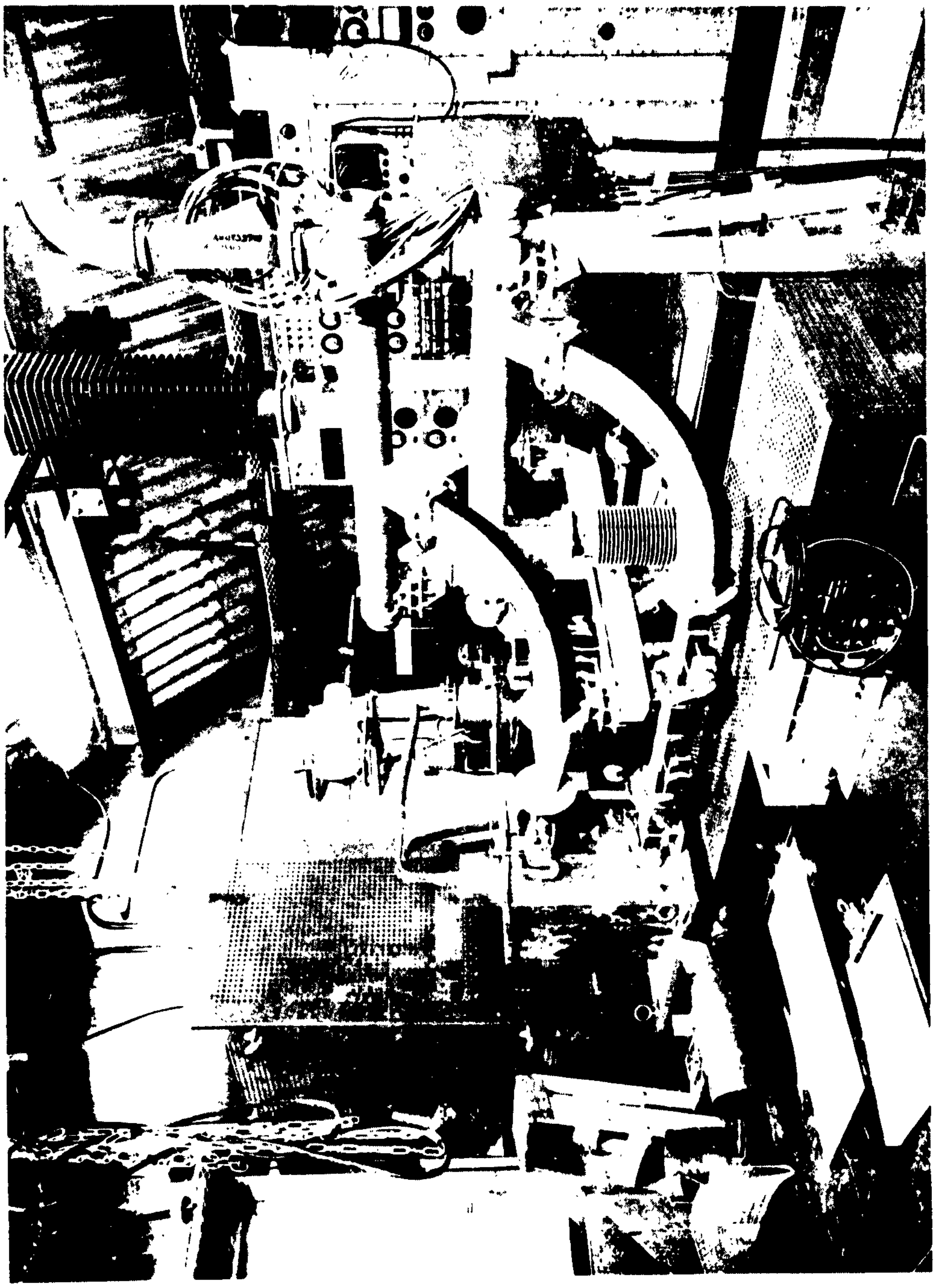

Fig 11 Two-Megawatt Klystrons

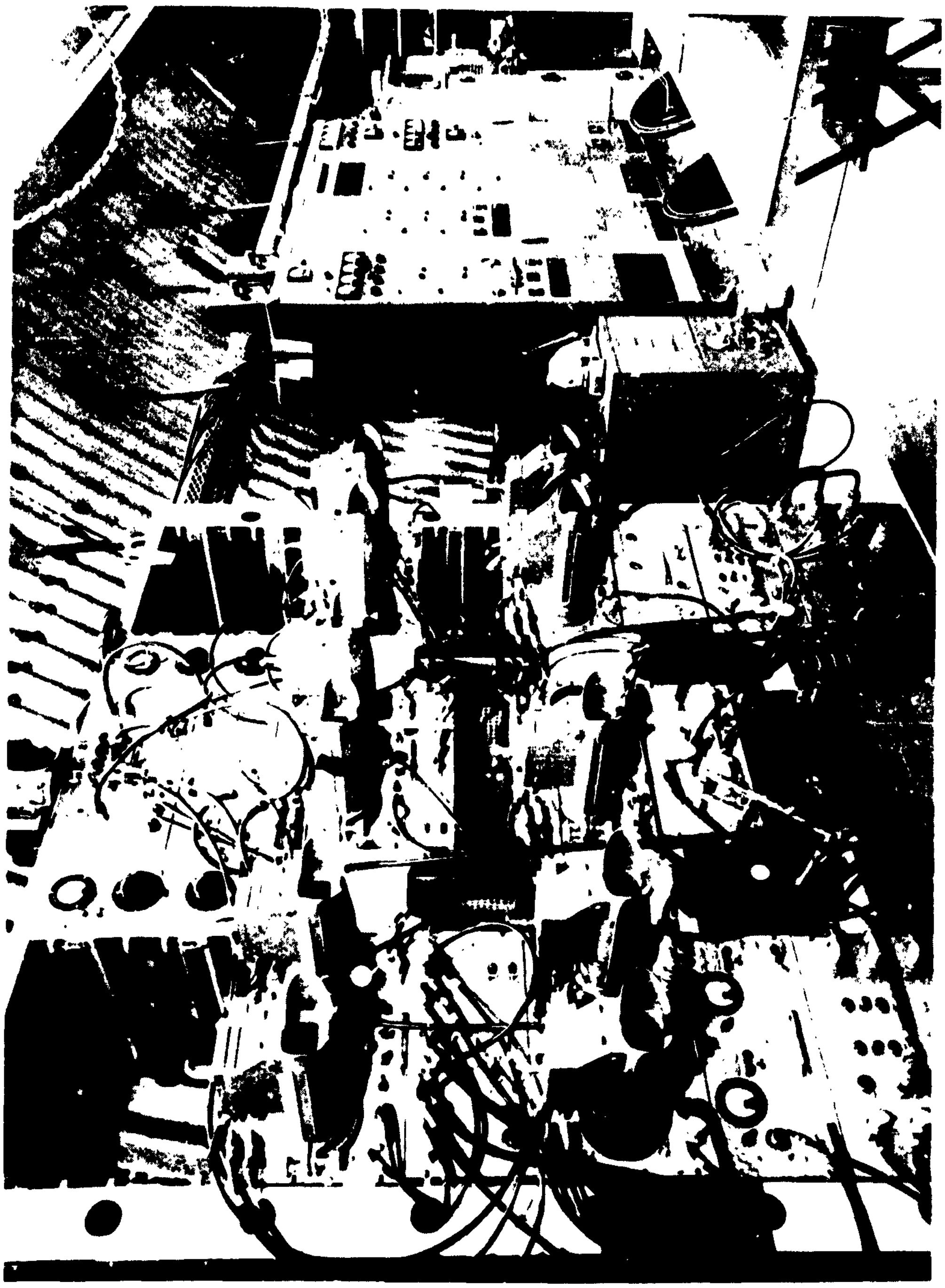

Fig 12   Data Recording and Timing and Amplifier Sections of Electronic System

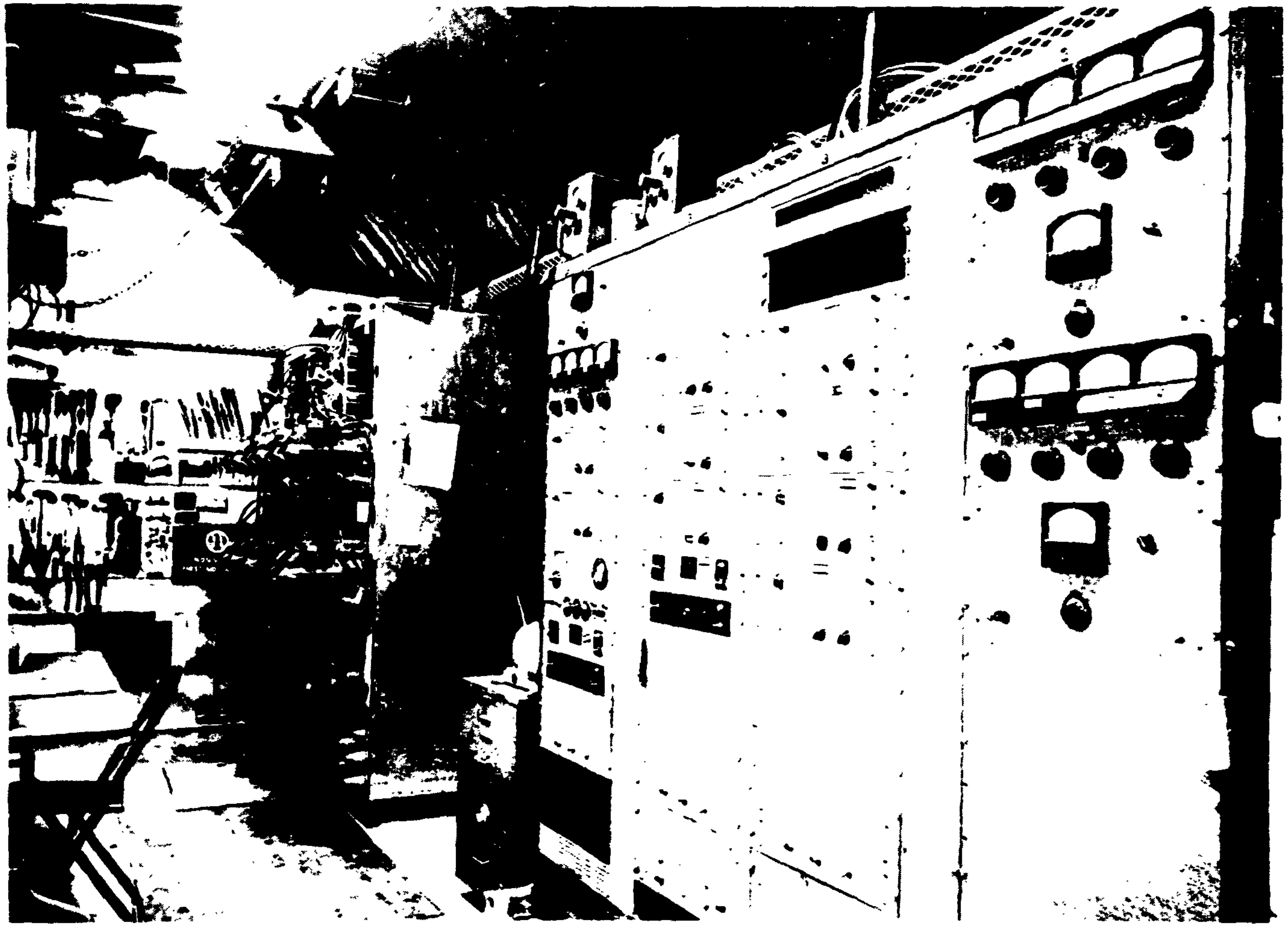

Fig 13 Data Recording and Timing and Amplifier Sections of Electronic System

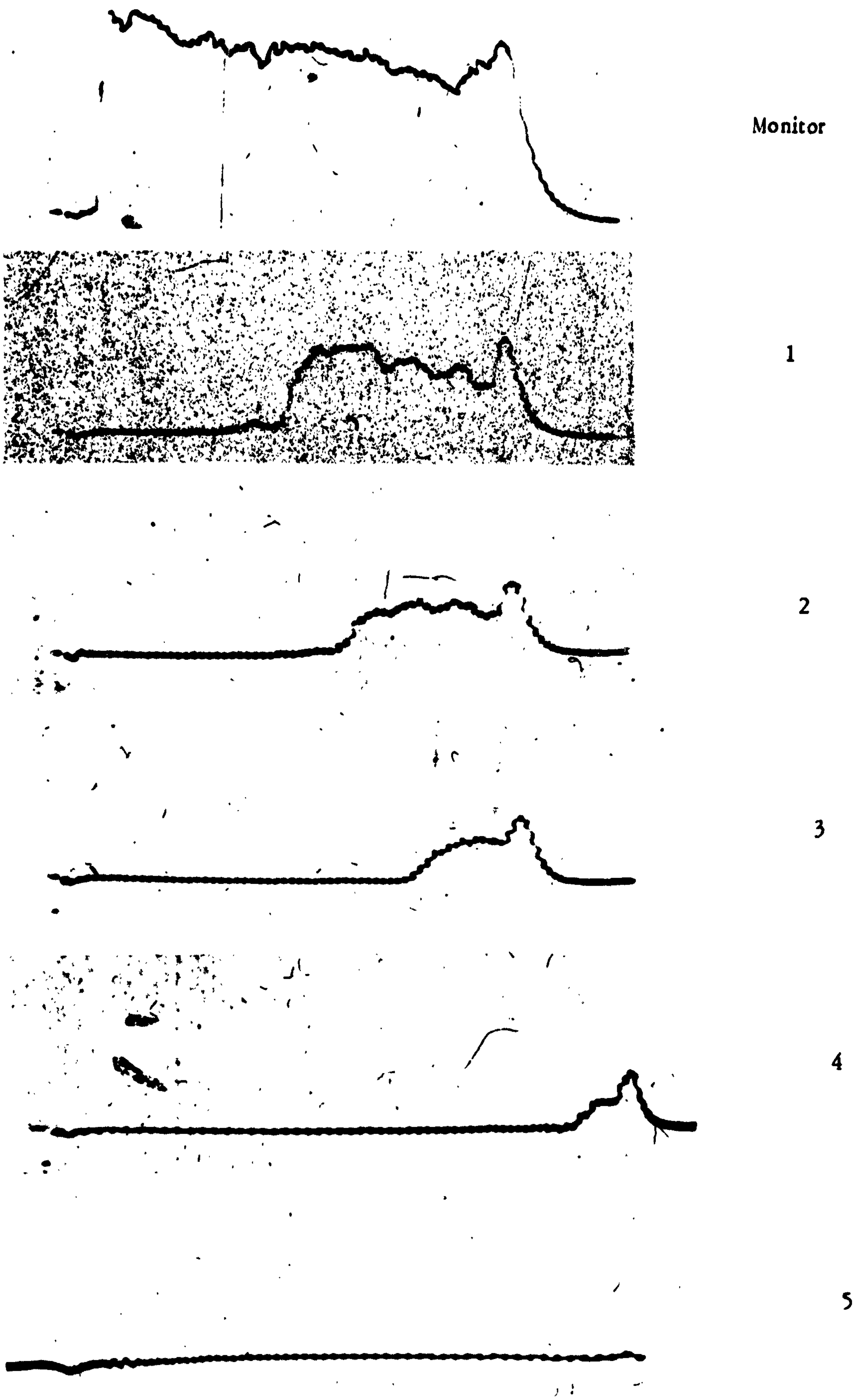

Fig 14 Oscilloscope Traces for Detectors

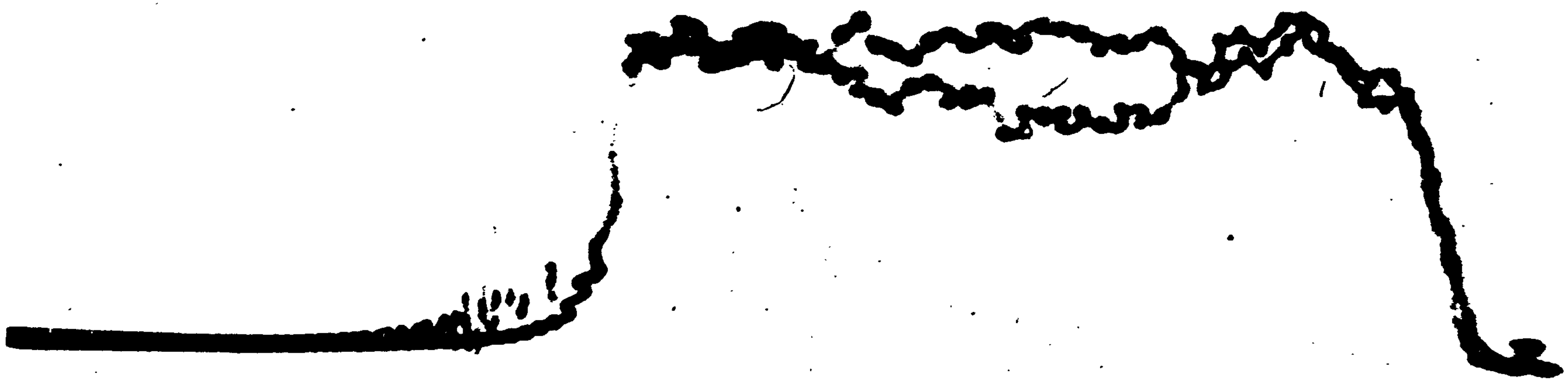

Fig 15 Linac Traces from Transmission Type Experiment

SOME APPLICATIONS OF DETONATION WAVE SHAPING

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INTRODUCTION

A field of primary interest to Aerojet's Explosive Ordnance operation has been the applied research and development of munitions incorporating the shaped charge principle. At frequent intervals during these researches, situations have presented themselves where detonation wave shaping has been found useful to improve performance of a marginal configuration, to create otherwise unobtainable target effects, or to permit effective utilization of components which are sensitive to the direction of detonation wave approach . Two of the more successful developments where wave shaping has proven beneficial are represented by the 7.0-inch T-42 shaped charge warhead for the Army's DART anti-tank guided missile and some earlier applied researches on the multiple-cone shaped charge warhead for the Navy TERRIER anti-aircraft guided missile. The former required wave shaping to increase performance of a marginal weight charge and to control the penetration hole shape, while the latter required wave shaping to control the direction and time of approach of the detonation wave front. The wave-shaping mechanisms employed in each of these munitions are described below.

APPLICATION OF WAVE SHAPING TO THE T-42 SHAPED CHARGE WARHEAD

The 7.0-inch T-42 shaped charge warhead included among its specifications requirements that the warhead weigh 20 lb, be a structural (full-size) member of the missile, and produce the maximum damage (in terms of mobility, firepower, and complete kills) on tanks armored with plate up to 5.5-inch thickness and at obliquities up to 70°.

Previous experimental studies[1] indicated that the most effective shaped charge weapon for the defeat of a tank was not necessarily one that would penetrate great thicknesses of armor. It was rather one that would defeat a reasonable thickness of armor (e.g., 5 to 8 inches), and then produce the maximum output and dispersion of high-velocity fragments beyond the

[1] D. R. Kennedy, G. C. Throner, et. al., *The Effects of Shaped Charges Beyond Defeated Armor,* NOTS TM462, 27 June 1952 (Confidential)

defeated armor, accompanied by the greatest side effects in terms of blast and incendiary effectiveness. Of the materials evaluated in the course of the referenced studies, aluminum appeared to be most effective as a medium- or large-caliber shaped charge liner. It was also established that to gain the most effectiveness from the aluminum liners, short standoffs (i.e., 1 to 2 cone diameters) were required. At these short standoffs, however, the penetration is inferior to that obtainable with other liner materials, and the standoff must be carefully selected to insure an adequate target overmatch. On the other hand, the increased penetration available at longer standoffs (i.e., 5 to 10 cone diameters) makes the aluminum liner attractive when external target impediments such as tool boxes, trigger plates, etc. are encountered by the weapon.

It was considered that the size (diameter) available for the projected DART weapon was sufficient to permit successful exploitation of the aluminum liner and further that such a material was probably necessary to permit the weapon to achieve the required levels of damage as set forth in the original specifications.

The considerable experimental work done with medium caliber (5-, 6.5-, and 8.5-inch diameter) aluminum shaped charges was all done with simple configuration, point-initiated, medium confinement charges. The explosive charges were as a rule at least 2.5 cone diameters long from the base of the cone; steel and aluminum cases of ⅛- to ¼-inch thickness were generally employed. The terminal ballistic evaluation of the performance of these charges was considered good and the spread between even diverse designs was not excessive. To design such a simple charge for the DART was a desirable goal; however, the stringent weight requirement coupled with a desire to make the warhead diameter equal to the full missile diameter precluded use of such a simple and essentially proven approach. For example, a warhead for DART designed according to the proven designs would weigh from 40 - 60 lb, which was well in excess of the 20-lb limitation imposed on the warhead. Therefore, one of the major problems encountered in the development of the DART warhead was to approach the excellent level of performance of the simple but heavy configurations with a warhead of one-third to one-half the weight.

To achieve the desired level of performance, the design was accordingly based on the premise of using light-weight structures to make as much of

the available weight either explosive or useful liner, and the use of certain known techniques to improve the performance of the charge. For example, the case and other purely structural components were designed to be as light and strong as possible. Since the DART missile is fabricated from glass- reinforced plastics and the warhead is an integral member of the structure, the decision was made to use such materials, if compatible with the explosives, for the main structure of the warhead.

Techniques available for improvement of the performance were restricted to those which were feasible, light in weight, not wasteful of space, and available within the state of the art existing at the time of the design. Of the several alternatives available to improve performance of a marginally designed or low-weight shaped charge, peripheral initiation appeared to be the most attractive, since it offered a potential increase in penetration (or at least a reduction in standoff required for a given penetration), and some control of the resultant penetration hole shape. For example, it was considered desirable that the hole produced in armor by the jet be divergent at least for the first several inches so that in attack against moderate thicknesses of target plate the jet and accompanying spall fragments would be more widely dispersed. Limited previous experience with detonation wave shaping by peripheral initiation indicated that this was a feasible goal.

Because of the requirement to keep parasitic weight to an absolute minimum, it was decided to use a light-weight air-barrier type of wave guide since the weight of lead oxide or other solid (e.g., glass, aluminum, etc) types of barriers would have been prohibitive.

In the design of the wave guide for the T-42, proper attenuation of the detonation front, so that it would describe a collapsing toroid over the cone and thus suitably alter the velocity gradient of the resulting jet, was of primary concern. Secondary factors in the design were ease of explosive loading around the barrier, minimum weight of barrier consistent with sufficient physical strength, and compatibility of materials used with the explosive.

Based on these considerations, the wave barrier design shown in Figure 1 was evolved. In this design, the wave guide consisted of a hollow, thin plastic case filled with foamed-in-place resin. The wave guides for the prototype rounds were made in a heated metal mold, the interior of which

was coated with a thin layer of a Glidpol polyester resin. After the resin jelled, Sta-Foam resin was poured into the interior of the wave guide shell where it subsequently foamed and set up.

The shape and thickness of the T-42 wave guide were determined from assumed values of shock transmission velocity through the plastic foam material which had been selected for the "air" barrier, and the paths that it was expected (on the basis of previous explosive lens design) the detonation front would travel. The position of the barrier relative to the liner apex was selected on the basis of the NOL peripheral initiation experiments[1] and several unreported follow-up experiments conducted at NOTS, which were based on the NOL work. It is now realized, with the benefit of hindsight, that the positioning may possibly not be optimum and that a barrier position closer to the apex may be superior. However, the obvious improvement in performance of the design selected, over non-wave-guided charges, and the necessity for early freezing of the design, precluded an extensive experimental program to determine the "optimum" position and wave barrier configuration.

It is significant, however, that even the earliest testing of the T-42 warhead indicated performance enhancement by use of the wave guide, since in this limited testing, single-shot improvements of hole volume and penetration were respectively 14% and 19% over the non-wave guided charge at the 7-inch standoff, and 58% and 16% respectively at the 13-inch standoff. (These values are for mild steel penetration and for Comp C-3 loaded charges. It should be noted that penetration hole volumes in armor plate averaged only about 63% that of mild steel.)

As noted above, during the initial design of the T-42 warhead it was necessary to make certain assumptions regarding the attenuation of the detonation shock wave which would be afforded by the wave guide. Not having firm experimental evidence available at the time, and lacking sufficiently accurate means for measurement, a nominal shock transmission velocity of 5000 fps was assumed for the foam-filled wave barrier. However, to insure a margin of safety, a 50% increase in thickness was incorporated into the wave guide design.

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[1]A. D. Solem and W. August, *Peripherally Initiated Shaped Charges*, NOL NAVORD 1772, 1 November 1950 (Confidential)

In the course of recent (June 1956) studies of wave shaping, a number of T-42 wave guides were tested to determine their effectiveness as used in the T-42 warhead. In the initial tests, three wave guides were tested as follows:

A $\frac{7}{16}$-inch-thick layer of Comp C-4 explosive was placed on the top surface of the wave guide, simulating the thickness of the explosive behind the device in the actual warhead. A 1-inch thickness of Comp C-4 was also positioned below and in contact with the under surface of the wave guide. To prevent the detonation wave from going around the barrier, the diameters of the two cylindrical pads of explosives were reduced to 4.75 inches (the barrier diameter is $5\frac{7}{8}$ inches). A 0.5-inch-thick, 0.75-inch-diameter tetryl pellet was positioned over the upper layer of the explosive (as in the warhead), and initiation was accomplished by a vertically positioned and accurately aligned No. 8 electric blasting cap. Each assembly was placed on top of a 1-inch mild steel plate and initiated. In all cases, detonation of the explosive under the barrier was accomplished, as evidenced by the heavy damage observed on the mild steel plate.

Since the original T-42 wave guide design concept only required that the barrier attenuate or delay the shock sufficiently to permit the surrounding H.E. to detonate in a path around the barrier, the above tests, while disturbing at first look, were not conclusive as regards the effectiveness of the barrier. Additional tests were then conducted using pin-switch and electronic-counter techniques to measure the actual delay time across the barrier. Also included in these additional tests was a T-42 barrier onto which had been fitted a $\frac{3}{16}$-inch-thick mild steel plate covering the entire upper surface (This was done at the suggestion of Dr. Sigmund Jacobs of the Naval Ordnance Laboratory.) In these tests, a setup similar to that used in the first tests was used, with the exception that a printed circuit pin-switch was placed at the two explosive-barrier interfaces so that the transient time of the shock across the barrier could be measured. Two Berkeley Counters connected in parallel were used to record the event. A transient time of 42 μsec was measured across the 2.75-inch-thick bare wave guide, while the steel-capped guide gave a 50-μsec delay. Tests were also conducted with a 2.5-inch thickness of Comp C-4, and transients of 7 and 10 μsec (.357 to .25 in./μsec) were recorded. Since these results are within the normally accepted range of detonation velocities of C-4, it was assumed that the measurements were reasonably accurate (Both

counters gave identical results for each of the shots.) The lower H.E. charge was initiated through the barrier in all cases tested. Since the path of the high explosive around the barrier is 2.8 times the thickness of the barrier, and the transient across the barrier is from 4 to 6 times as slow as the H.E.detonation, a comfortable margin apparently exists to allow the detonation wave to go around the barrier (21 to 31 μsec) before the shock wave reaches the explosive through the barrier (42 μsec).

These data, while representing small samples, indicate that the initial assumption of 5000 fps should perhaps be corrected to approximately 5460 fps for the T-42 barrier, as designed. The expression "as designed" is emphasized since it appears likely that the hardened plastic outer shell of the wave guide may contribute to the delay and explosive initiating characteristics noted. Tests with bare sheets of Styrofoam, which is similar to the foamed Sta-Foam material used in the T-42 wave guide (although of slightly greater density) revealed that extremely long delay times are possible with this material and that detonation of the H.E. protected by low-density foamed plastic is probably unlikely, which is the reverse of the situation with the wave guide used in the T-42. Two such tests were conducted using explosive thicknesses identical to that used in the wave guide tests, but with a 2.5-inch thickness and a 1-inch thickness of sheet Styrofoam respectively. The detonators in these latter tests were laid parallel to the Styrofoam-H.E.sandwich to prevent direct initiation through the foam by the jet originating from the detonator. (Vertically oriented detonators, as employed in the T-42 warhead were used in the actual wave guide tests to simulate true conditions as accurately as possible.) In the latter tests, delay times of 4716 μsec (both counters) were obtained for the 2.5-inch-thick barrier, and 1771 and 1835 μsec were recorded for the 1-inch-thick barrier. Initiation of the lower explosive was obtained through the 1-inch barrier only. Plotting these few data from 0 as a function of delay vs thickness gives a straight line, although considerably more tests of these materials should be conducted before any statistical significance can be given to these data or that from any of the other described tests.

In summary, it appears that the T-42 wave guide as presently designed allows the shock wave (or possibly the jet from the detonator) to travel only 1.4 to 2 inches of its 2.75-inch thickness during the time that the detonation in the surrounding explosive goes completely around the barrier to accomplish the desired collapsing toroid wave front for the attack of the shaped charge liner.

APPLICATION OF WAVE SHAPING TO THE MULTIPLE-CONE SHAPED CHARGE WARHEAD

Experimental investigation of the multiple-cone shaped charge for possible adaptation in the TERRIER anti-aircraft warhead was conducted at NOTS, Inyokern, during the period 1952 - 1953. This work preceded the current studies being conducted by the University of Utah with the metal-air-gap initiation system as reported elsewhere in the transactions of the Wave-Shaping-Conference.

The basic test warhead configuration consisted of a cylindrical section of 11.75 inches outer diameter by 22 inches length (Fig 2). Embedded in this cylinder were forty-five 4.25-inch-diameter aluminum conical liners arranged in five rows of nine cones each. The cone pattern was further arranged in a spiral so that a jet would be produced every 8 degrees about the warhead circumference. To insure projection of each jet normal to the warhead surface and prevent interference between adjacent jets, it was considered necessary to control the detonation wave front so that it would approach all cones normal to their apex and as nearly simultaneously as possible.

Several alternative approaches were considered, including rudimentary concept of the metal-air-gap lens, a system of folded equi-length primacord leads, and a system involving the simultaneous initiation of a number of electric detonators.

The metal-air-gap lens concept, although offering the least complicated wave-shaping system, was just beginning to be explored in connection with delay detonator systems by Breslow, Smith, et. al., at NOTS, Inyokern, and hence was not then backed by sufficient experimental data to permit design of a system for the multi-shaped-charge warhead.

The equi-length detonating cord system was demonstrated to be feasible in the simultaneous firing of groups of five adjacent parallel-oriented shaped charges. However, the small central cavity available for the initiation system in the multiple shaped charge warhead rendered packaging of such a system most difficult, particularly when five centers of detonation were required.

It was, therefore, considered that the approach to be followed was to

seek a relatively simple electric system wherein five electric detonators would be fired, as within a total time spread not to exceed 1 μsec. The resulting design consisted of a cylindrical arrangement with five "spool"-shaped tetryl boosters located at each plane of apices of each row of shaped charge cones (Fig 3). The five electric detonators were oriented along the horizontal axis so that the output end of each detonator pressed against the reduced thickness center web of each spool-shaped booster (Fig 4). The electric leads from each detonator were led past each of the other assemblies so that all leads met a common terminal at one end of the warhead.

An appreciable effort was expended in determining, first of all, which available electric detonators were inherently accurate, and secondly, which type of hookup, i.e., series or parallel, and what level of energy must be supplied. It was soon determined, through rotating-mirror streak camera studies, that commercially obtainable electric blasting caps, including even seismographic caps, were unsuitable because of their inherent delays and that a carbon-bridge type detonator was best suited for the application. The final system evolved employed NOL-developed XE12B detonators in a series hookup and driven by a 1500-V discharge from a capacitor located at the warhead. With this system, simultaneities of 0.1 μsec for the five-detonator-booster assembly were obtained and it was considered that this was more than adequate to successfully detonate the warhead.

No complete warheads were fired with the 0.1-μsec spread initiator system. However, warheads fired with systems of less simultaneity (Fig 5, end view, Fig 6, side view) indicated that simultaneous axial initiation was desirable not only for the directional control of the jets produced from the shaped charges but for improving the blast efficiency of the warhead. Since the warhead was detonated from the center outward, rather than along its longitudinal axis, the time required for the detonation of the contained explosives was shortened, with a consequent increase in peak pressure.

It is believed that many items of explosive ordnance, particularly cylindrically shaped blast and fragmentation warheads having fineness ratios higher than unity, can benefit by wave-shaping techniques which provide simultaneous axial initiation or control of the detonation wave front for the most advantageous approach to the fragment wall. Of the

systems described briefly on the previous page, it is probable that the metal-air-gap lens system being developed by the University of Utah holds the most promise because of its simplicity and adaptability to irregular or ogival-shaped ordnance.

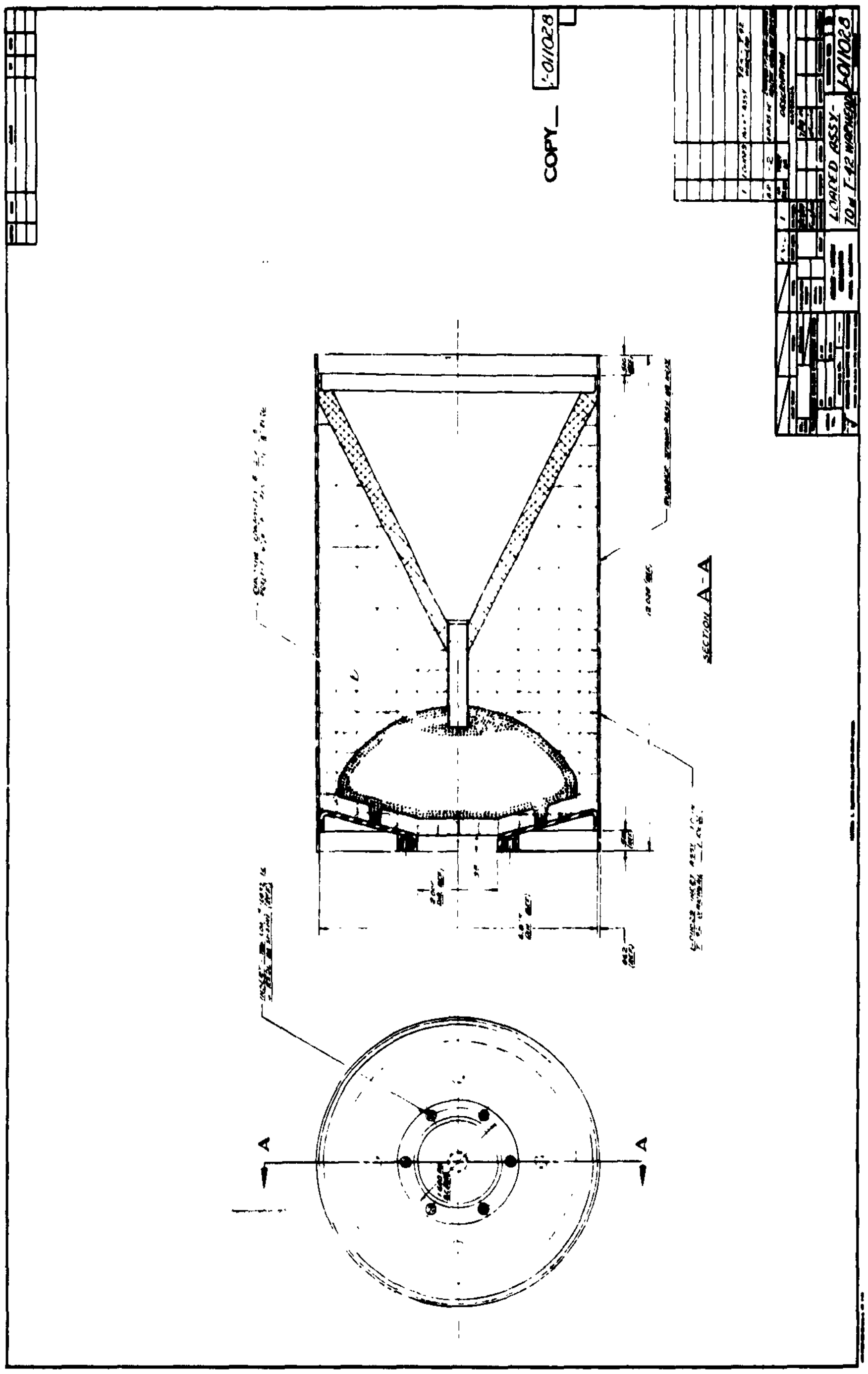

Fig 1 T42 7.0-Inch Shaped Charge Warhead

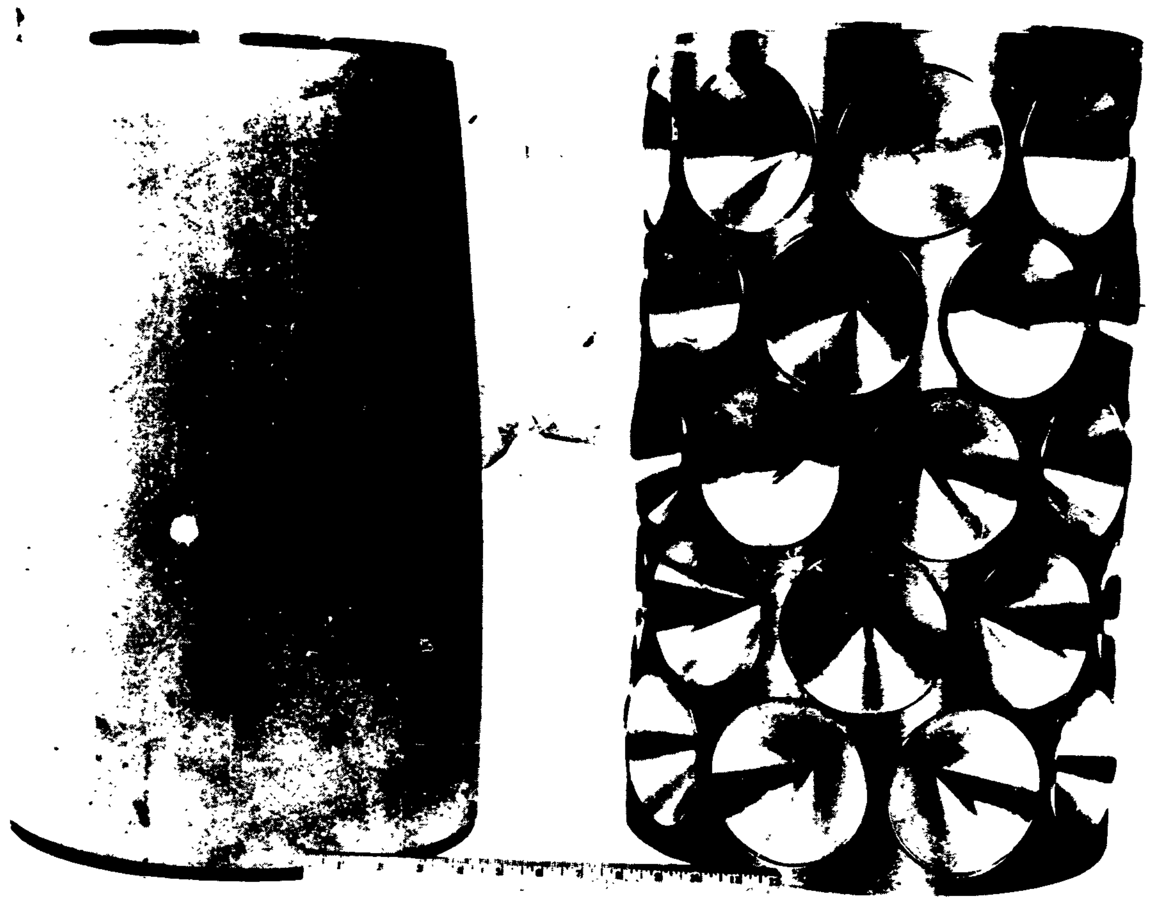

Fig 2 Multiple-Cone Shaped Charge Warhead

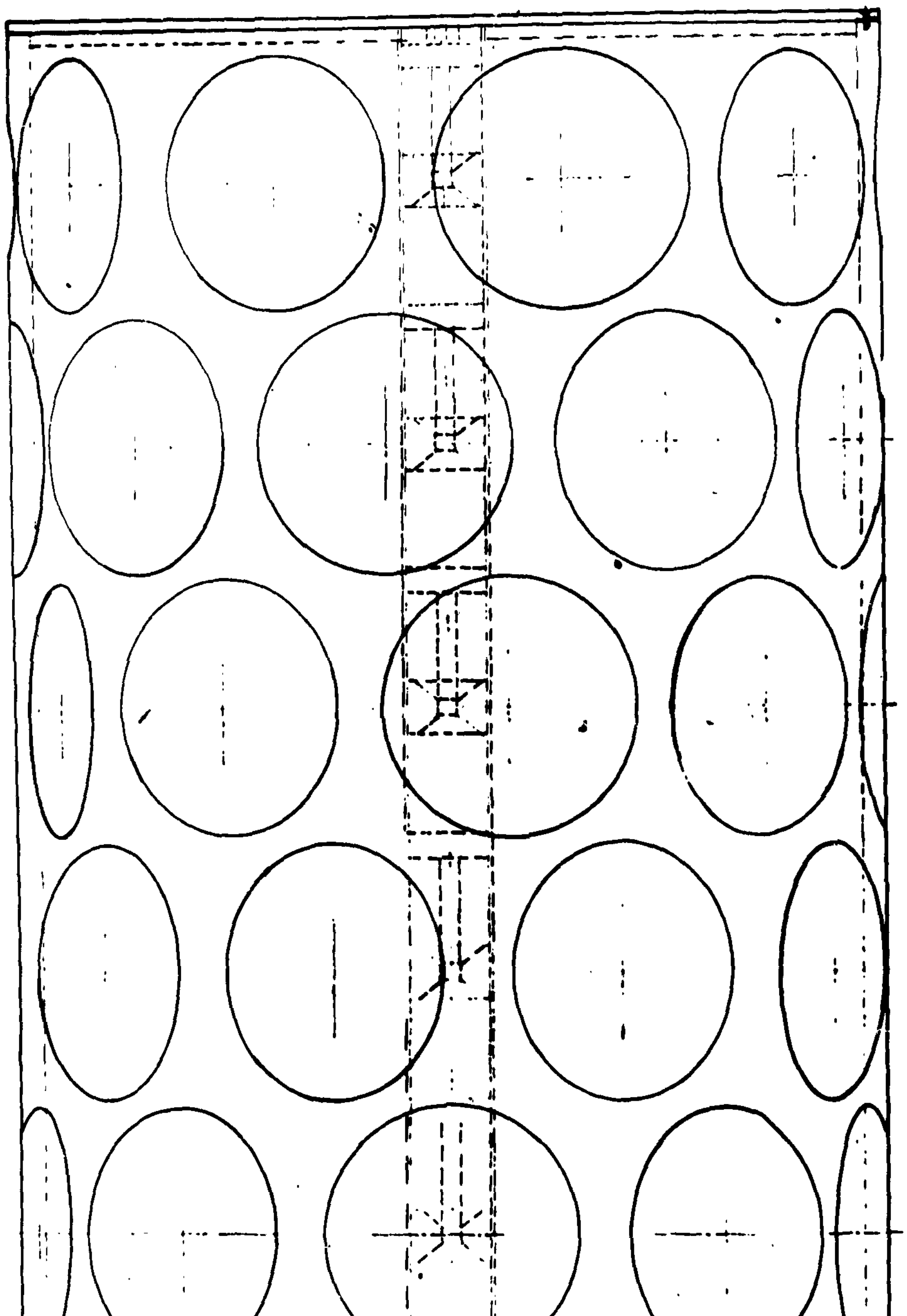

Fig 3 Diagram Showing Location of Boosters in Warhead

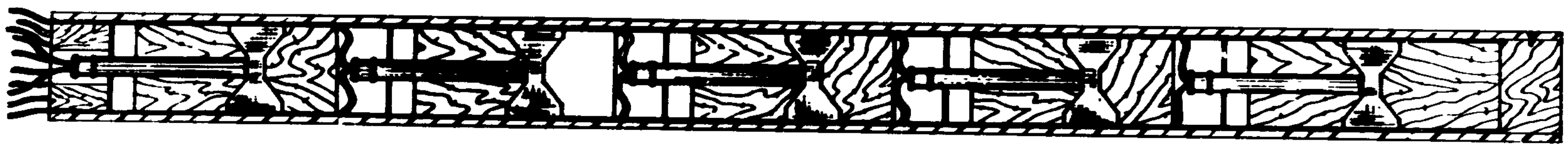

Fig 4 Arrangement of Boosters and Detonators

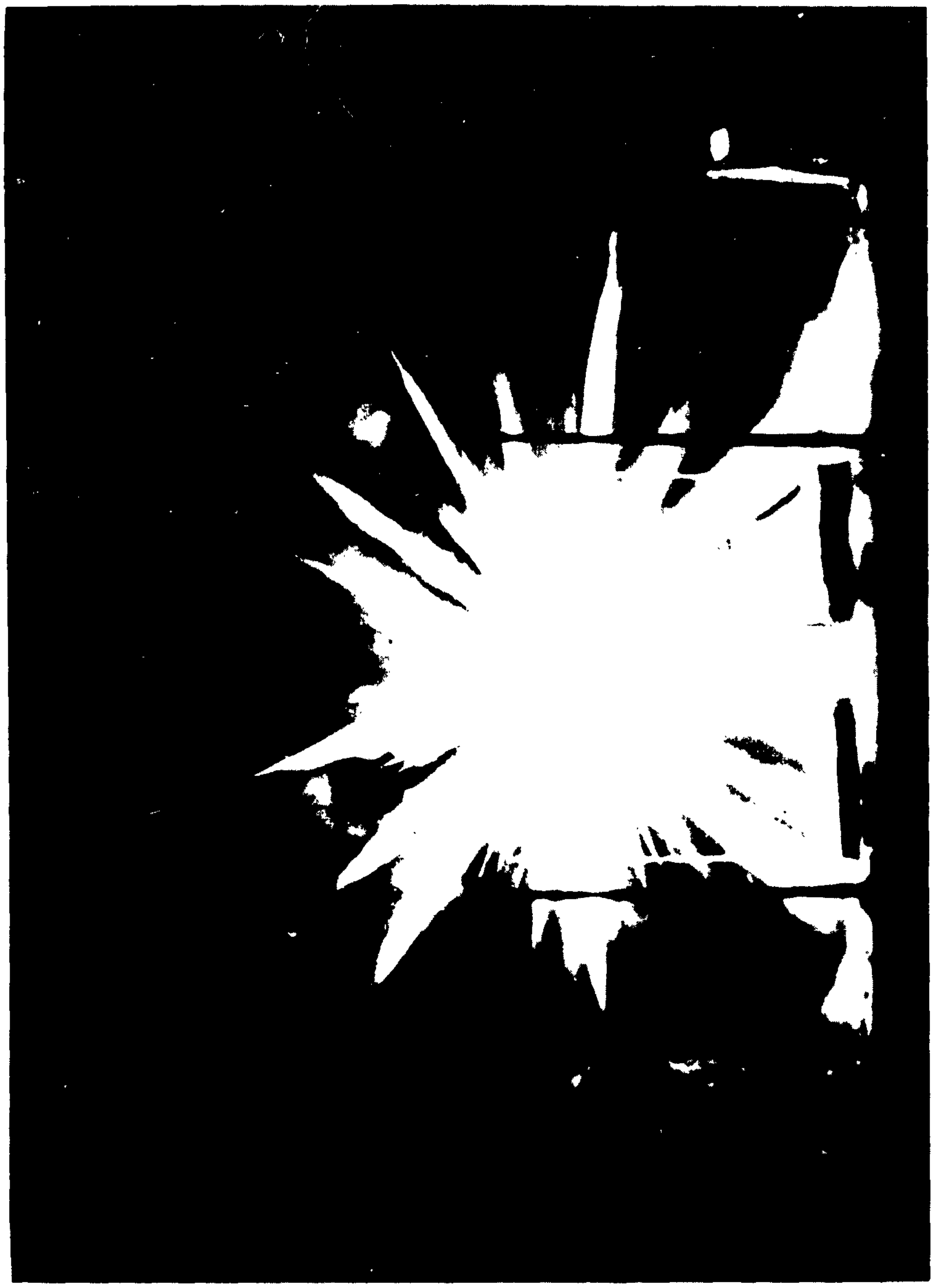

Fig 5   End View of Firing of Warhead

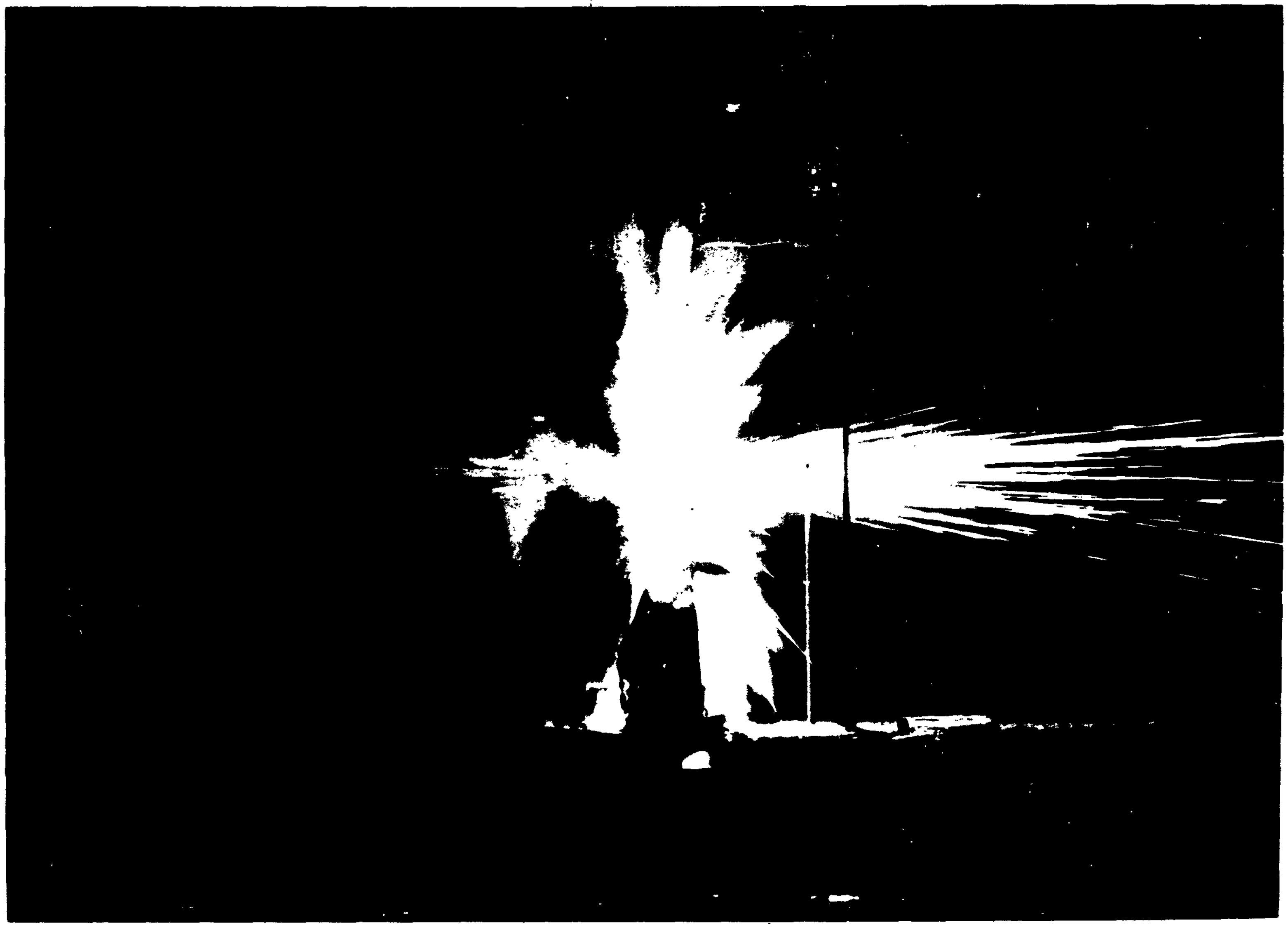

Fig 6 Side View of Firing of Warhead

INITIATION OF EXPLOSIVES THROUGH METAL BARRIERS

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ABSTRACT

Two cylindrical explosive charges separated by steel d: s of varying thicknesses were used in a series of tests in which one explosive charge was detonated to obtain a "low order" detonation wave in the explosive charge on the opposite side of the steel disc. The acceptor charge showed that as the plate thickness increased, the length of travel of the "low order" wave and the time to high-order detonation increased. No high-order detonation occurred where an explosive-to-metal length ratio of greater than 3:2 was used.

When the high-order detonation wave traveled back through the region traversed by the "low order" wave the velocity showed a slight decrease from stable high-order detonation velocity, but the decrease did not appear to be significant. There are some indications that an additional effect may be obtained when a high-order detonation wave is passed through a "low order" region; however, this part of the tests was inconclusive.

INTRODUCTION

For several years there has been considerable interest in controlling the shape of the detonation wave in high explosives. A great many investigators have contributed to the store of knowledge which has been compiled regarding this phase of explosive phenomena. Aside from the value of a better understanding of the mechanism of propagation and initiation of high explosive, the study of the shape of the detonation wave has also furnished much useful information on behavior of materials subjected to explosive impact. Two of the many examples which could be mentioned are: (1) the experiments regarding the dependence of detonation velocity upon charge diameter (Ref 1) and (2) the experiments using peripheral initiation to enhance the effect of shaped charges (Ref 2).

Recently a new and rather intriguing explosives effect was reported (Ref 3), namely, that greater efficiency can be obtained from a high

explosive if a stable detonation wave is passed through a region during or immediately after the passing of a "low order" detonation wave through that same region and prior to expansion of the "low order" detonation products.

It was the purpose of this investigation to conduct a number of experiments in an effort to assay this reported effect and to determine its applicability to existing explosive ordnance. The preliminary stage was conducted to experimentally investigate the parameters necessary for a "low order" detonation. The term "low order" is in itself a controversial issue but we shall define it here to mean an unstable shock wave in Composition B.

EXPERIMENTAL ARRANGEMENT AND RESULTS

The experimental arrangement shown in Figure 1 was used. For each test, two standard cylindrical charges of Composition B (2 1/8 in. diameter x 3 in. long) were separated by a 7-in.-diameter steel plate. For successive firings the thickness of the steel barrier plate was increased until the lower charge failed to detonate. When this condition was reached it was then planned to synchronize the initiation of the lower charge so that a stable detonation wave would pass through the lower charge during or immediately after the passage of the stress or shock wave caused by the upper charge. As is indicated below, this specific synchronization was not necessary due to the somewhat unexpected results obtained with the lower or receiver charge.

A high-speed rotating-mirror streak camera was used to observe the firing of the test charges. The standard test charge was placed in a vertical position such that the camera slit covered the center of the charge vertically as shown in the streak photographs. In the first standard test conducted a 3/4-in.-thick steel barrier plate was used. Examination of the streak camera photograph showed that high-order detonation of the lower charge did not occur at the explosive-metal interface as was expected but rather at some distance from the interface. This observation rendered unnecessary the synchronization phase of this experiment mentioned above since the photograph showed that a high-order detonation wave passed upward from the point of initiation of the lower charge through the region previously traversed by a shock or stress wave. The distance upward from

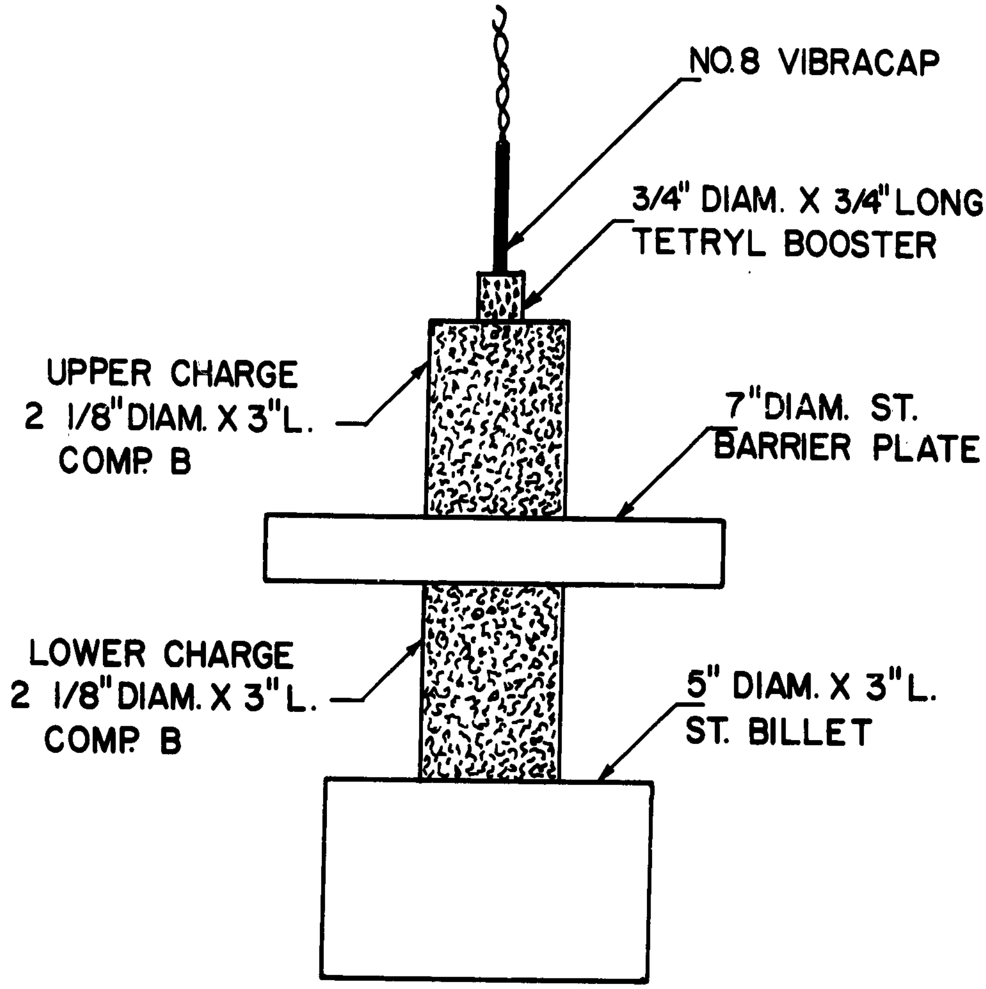

Fig 1 Standard Test Charge

the point of initiation of the lower charge to the explosive-metal interface (designated X, as shown in Fig 2) was approximately 1.5 centimeters. The image on the streak camera photograph was so short that measurements were difficult to make. Therefore, the next barrier plate thicknesses used were 1 in., 1 1/4 in., 1 1/2 in., and 1 3/4 in., respectively. Standard test charges were assembled with these barrier plates and fired. Streak camera photographs were taken of each firing. The streak camera film showed that as the barrier plate thickness (l) increased, the initiation distance (X) and the delay in initiation (t) increased. The letter (t) is used to designate the difference in time between the arrival of the stress wave at the explosive-metal interface and the beginning of high-order detonation.

A sample calculation taken from the streak camera record in Figure 6a can be used as a typical example. The total delay in initiation of the lower charge is equal to C_f (see Fig 2) divided by the writing speed of the camera (57 mm divided by 3.124 mm/μsec equals 18.25 μsec). The velocity of a stress wave in steel is about 0.234 in. per μsec (Ref 4). Therefore, the time delay due to the barrier plate is about 6.41 μsec. The actual delay in detonation if caused solely by this stress wave is about 11.84 μsec.

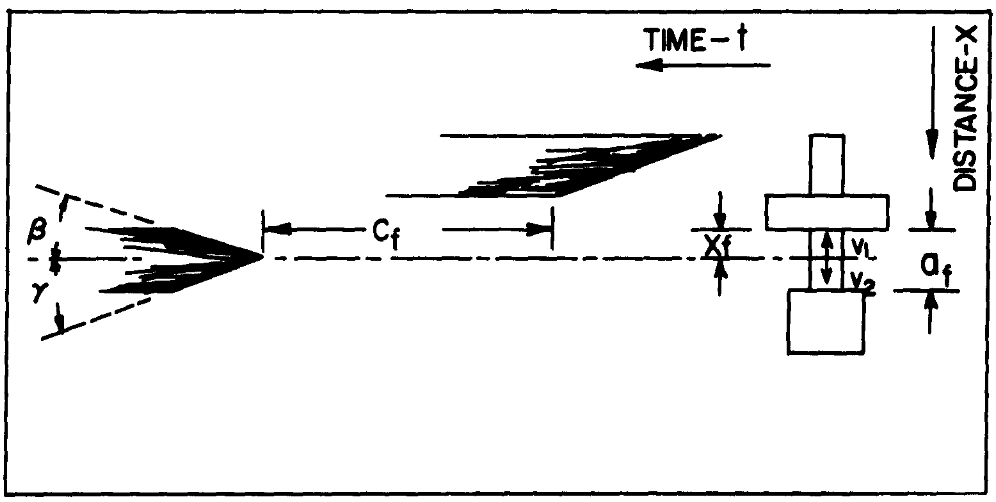

Fig 2 Symbols and Measurements used in Table 1

A number of standard test charges with barrier plate thicknesses ranging from 3/4 in. to 2 in. were fired to obtain a representative curve

of initiation distance (X) versus initiation delay (t) and also to give more precise data on velocities associated with the high-order detonation wave (V_1) from the initiation point upward. The data on these firings appear in Table 1. The graph of initiation distance (X) versus initiation delay (t) using the data appearing in Table 1 is shown in Figure 3.

DISCUSSION OF RESULTS

To explain why the shock wave has to travel a finite distance in the lower charge before a stable detonation is initiated will require a rather detailed analysis of the initiation distance (X) versus initiation delay (t) graph. Although the data points tempt one to draw a straight line it can be shown that this would be incorrect; i.e., a straight line would intersect the (x) axis above the origin indicating an infinite velocity when infinitely thin barrier plates were used. It is obvious that at the origin the slope of the velocity curve would be equal to the detonation velocity of the explosive and must also go through the origin. Since there is no reason to believe that this is a discontinuous function the velocity line must have a finite radius of curvature which decreases as it approaches the origin. The slope of a line drawn from the origin to any point on the curve of Figure 3 represents the average velocity in the lower charge of the shock wave between the explosive-metal interface and the point of initiation.

It is reasonable to assume that as the barrier plate thickness is increased the intensity of the shock wave entering the lower charge is decreased. If it is also assumed that the shock wave entering the lower charge is above a minimum intensity it will be supplemented by a chemical reaction; the pressure build-up from the reaction is dependent upon the shock intensity. Therefore, when thin barrier plates are used the initial shock intensity is high, the pressure build-up from chemical reaction is fast, and so initiation takes place near the explosive-metal interface. When thicker barrier plates are used the initial shock intensity is lower, the pressure build-up from the chemical reaction is slower, and initiation takes place farther from the explosive-metal interface.

The velocity curve looks much like a hyperbola that approaches an asymptotic line with a slope of 2.54 mm/μsec. This value represents a shock wave velocity below which initiation cannot occur.

It is instructive to examine the velocity upward (V_1) from the point of initiation in the lower charge. If it is assumed that a partial chemical reaction accompanies the shock wave, then it might be expected that an increase in pressure would occur provided there is no expansion of the reaction products. If these conditions exist it might be argued that the velocity of detonation could be higher than normally observed. In fact some of the streak camera records show an abnormal velocity situation such as is shown in Figure 5a. From the point of initiation upward the trace appears to rise very sharply near the explosive-metal interface indicating a velocity greater than the stable detonation velocity in Composition B. However, it should not be inferred that this is the only explanation for the sharp rise in the trace since this was only observed in a few [illegible]raphs where thin (3/4 in.) barrier plates were used. This may lead [illegible] conclusion that confinement plays an important role in a higher than normal detonation velocity.

When finally evaluated, however, this set of tests led to inconclusive results. The final evaluation was to obtain an average velocity of (V_1) which showed a difference from that of stable detonation velocity in Composition B. Evaluation of this type was made difficult because as previously stated it may only take place under extreme confinement conditions such as with the thin barrier plates where (X) is small and the trace very short. When thicker barrier plates were used and the distance (X) was long so that it was easy to obtain velocity measurements, velocity between (V_1) and (V_2) as averaged over the whole series of tests was approximately 2000 fps below average detonation velocity. This is small enough to be within experimental error, and is therefore inconclusive.

Another reason why the results appear to be inconclusive is the fact that when thicker barrier plates were used and a long trace obtained, the trailing edge of the trace showed a slower velocity than the leading edge. This could be explained by expansion of the partial reaction products at some distance from the point of initiation.

Figure 4 shows the curve obtained when the barrier plate thickness (l) is plotted against the initiation distance (X). It is related to the energy required to initiate a shock wave in high explosive of sufficient intensity to lead into a high-order detonation. As yet a full analysis of this curve has not been made. It is presented merely to clarify the remarks made in this paper.

As can be seen from Figure 4 the curve approaches an asymptote that is parallel to the (X) axis as barrier plates of slightly more than 2 in. are used. This in itself is enough to say only that these particular parameters of explosive and metal give approximately a 3:2 ratio beyond which no detonation will occur. The tests have not been extensive enough to attempt to write a scaling law for different explosive-metal parameters.

CONCLUSIONS

No attempt was made to interpret the data quantitatively although by judicious use of plane shock wave theory and stress wave analysis it looks as though the data might be quite useful for this purpose. Regardless of its quantitative use this series of tests gives us a better qualitative picture of what happens in "low order" detonation, how it can be attained, and how it progresses into a high-order detonation.

When the high-order detonation wave travels back through the region traversed by the "low order" wave the velocity shows an insignificant decrease from stable high-order detonation velocity. The streak camera photographs show a lateral expansion of the "low order" detonation products which could account for the decrease in velocity. There are some indications that an additional effect may be gained by passing a high-order detonation wave through a "low order" region. A few of these indications have been observed in tests run in conjunction with the tests reported here but are not included in this report. The only indication in this series of tests was the apparent increase in velocity near the explosive-metal interface when thin barrier plates were used. This implies that confinement is an important factor, but its role has not yet been evaluated by the authors.

The authors wish to gratefully acknowledge the advice and assistance of Dr. R. H. Olds in the interpretation of the experimental results.

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TABLE 1

Test Charge Data

l (mm)	A_f (mm)	X_f (mm)	C_f (mm)	C (μsec)	d (μsec)	t (μsec)	X (mm)	β (deg)	γ (deg)	V_1 (fps)	V_2 (fps)	n
19.05	10.55	2.00	26.38	8.44	3.20	5.24	14.45	19.45	19.18	26122	25752	4
25.40	10.80	2.75	36.13	11.57	4.27	7.30	19.40	17.25	19.23	22516	25268	4
31.75	10.60	3.25	44.25	14.16	5.34	8.82	23.36	17.28	19.65	22921	26311	4
38.10	10.67	3.96	54.14	17.33	6.41	10.92	28.28	18.29	21.01	24156	28109	7
44.45	10.64	5.60	72.06	23.07	7.48	15.59	40.11	17.59	22.56	23268	30534	9
47.63	10.70	9.50	113.00	36.17	8.01	28.16	67.65	17.67	---	23214	----	3

l = barrier plate thickness
A_f = charge length measured from film as shown in Figure 3
X_f = distance on film from explosive-metal interface to initiation point as shown in Figure 3
C_f = delay in initiation as shown in Figure 3 (measured from film)
C = C_f divided by mirror writing speed of 3.124 mm/μsec
d = time for stress wave to travel through 1 mm of steel at 19,500 fps
t = actual delay in initiation (C - d) or time as measured from stress wave arrival at explosive-metal interface to initiation
X = actual vertical distance from explosive-metal interface to initiation point
β = angle as shown in Figure 3
γ = angle as shown in Figure 3
V_1 = detonation velocity from initiation point upward (Fig 3)
V_2 = detonation velocity from initiation point downward (Fig 3)
n = number of tests with each barrier plate thickness

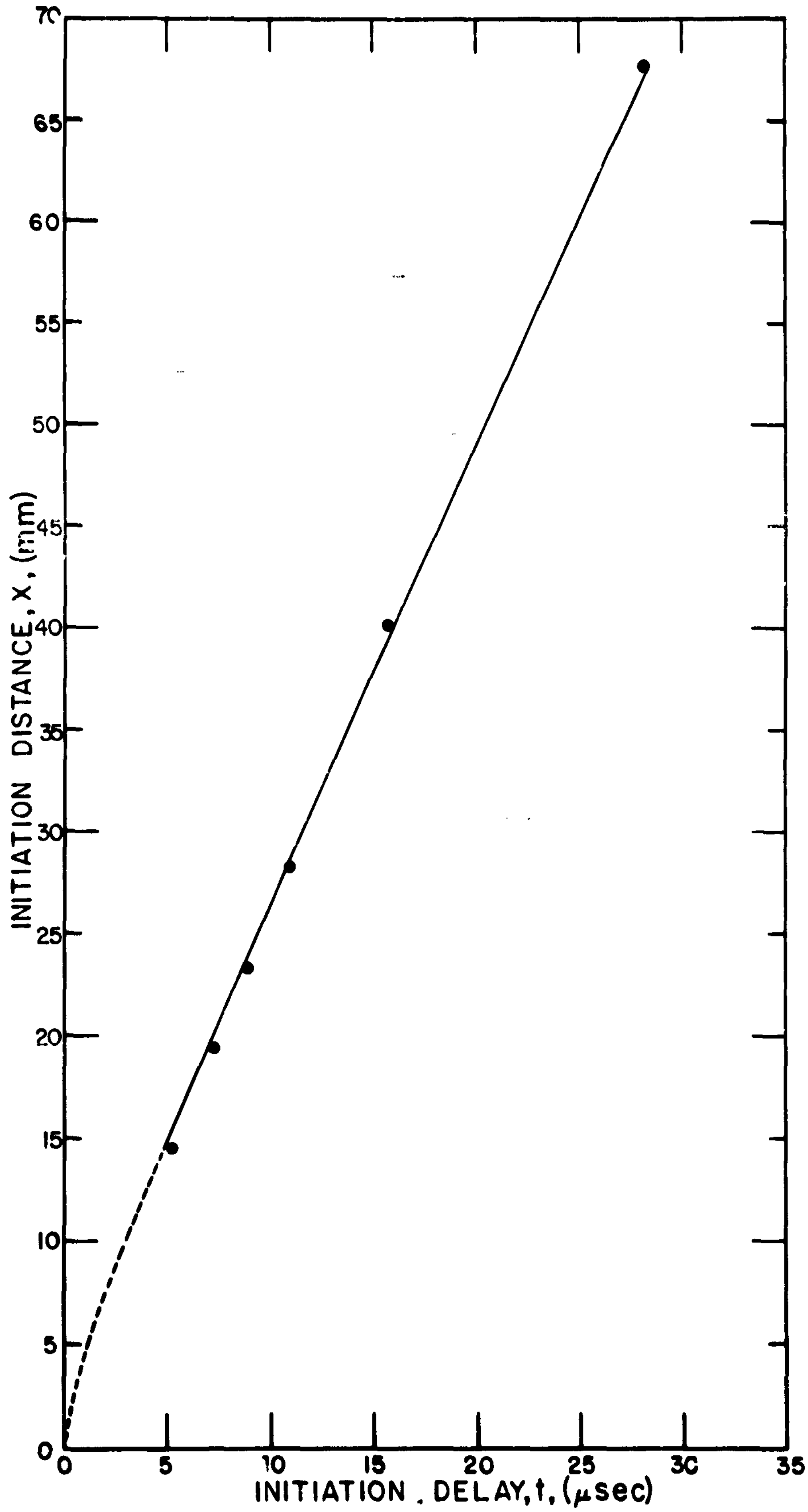

Fig 3 Plot of Initiation Distance (X) versus Initiation Delay (t)

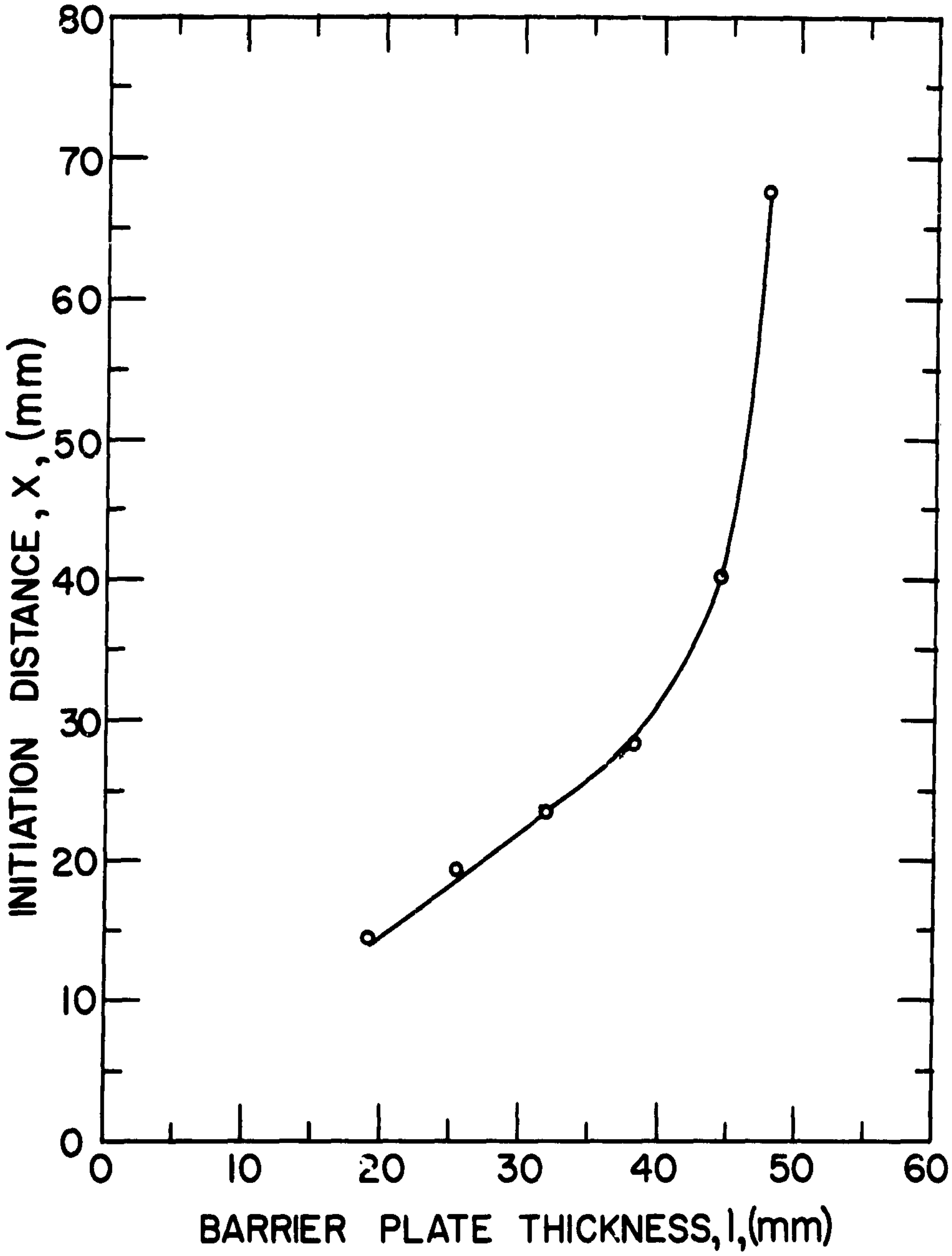

Fig 4 Plot of Barrier Plate Thickness (l) versus Initiation Distance (X)

Fig 5a

Fig 5b

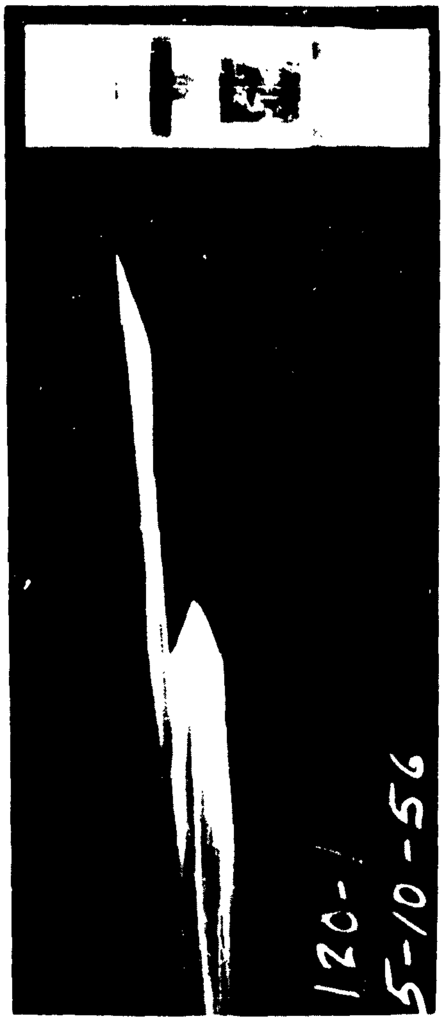

Fig 6a

Fig 6b

A THEORY CONCERNING THE INITIATION OF DETONATION BY SHOCKS

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The photographic evidence presented at this meeting by M. Sultanoff (BRL) and L. Cosner (NOTS) rather st gly suggests a theory of initiation by shocks which will be presented here. I believe this theory can explain not only their experiments, but most, if not all, of the experimental work presented at this meeting as well as elsewhere when boundary effects are taken into account. In its simplest form we can consider the initiation in one-dimensional transient flow. We can consider that the explosive has been shocked by a square step impact due to a shock in another bounding medium or an impact by another medium. The result of the shock is to increase the pressure, p, and temperature, T, at the boundary and to set the explosive in motion with a particle velocity, u. The rate of reaction may be considered to be a function of all three variables, but temperature probably will predominate in determining the rate. In any event T and u will be determined by the transmitted pressure at the time reaction begins.

Let the transmitted shock velocity be denoted by U and let c denote the speed of sound in the medium. The sum of u + c behind the shock should be greater than U for a well behaved shock. When the shock wave passes a given particle the rate of reaction suddenly increases. This increase in rate appears, therefore, first at the boundary. After a time, dt, the reaction will have released some energy in the region passed over by the shock. A consequence of this energy release will be a further increase in temperature and pressure. The pressure incre e will be transmitted forward in a wavelet which will move at a velocity (u + c) + d(u + c). (Some care will have to be exercised in defining c when reaction occurs.) This wavelet will increase the pressure and temperature at the shock front upon overtaking the latter. The reaction at points removed from the boundary will therefore be started at a higher rate and completed faster. This will further increase the pressure by compression waves overtaking the shock front at higher and higher values of u + c until some point will be reached when the reaction rate is about that of a normal steady detonation. The shock velocity velocity will thereby acquire the velocity, D, of a steady detonation in this overtaking wave process. The conditions are illustrated in Figure 1.

Details for many boundary conditions will have to be worked out. Experimentally, rarefactions will likely follow the shock so that reaction is completed first at some point removed from the moving boundary. This leads to the results observed by Cosner and Sultanoff and the retonation or receding detonation wave through a partially reacted region as seen in some of the records. The case where spherical or cylindrical expansion occurs, as described by Dr. Poulter, may be similarly explained in a qualitative way.

This theory is essentially the same as that used to explain the detonation which sometimes develops ahead of a deflagration wave in gases. The boundary displacement in that case is due to the expansion of the products of combustion causing mass motion ahead of the flame front. When the particle velocity gets high enough in front of the flame the waves can coalesce to form the new "hot center" from which a forward facing detonation and a backward facing detonation or retonation can develop. Figure 304, 304a, in Lewis and von Elbe[1] is a nice illustration of the formation of a detonation due to compressive waves. The discussions on pages 612 and following suggest the relation of compressive waves to detonation formation even though no details are given for a case similar to the pure shock initiation of concern to us here.

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[1]B. Lewis and G. von Elbe, *Combustion, Flames and Explosions in Gases*, New York, Academic Press, 1951

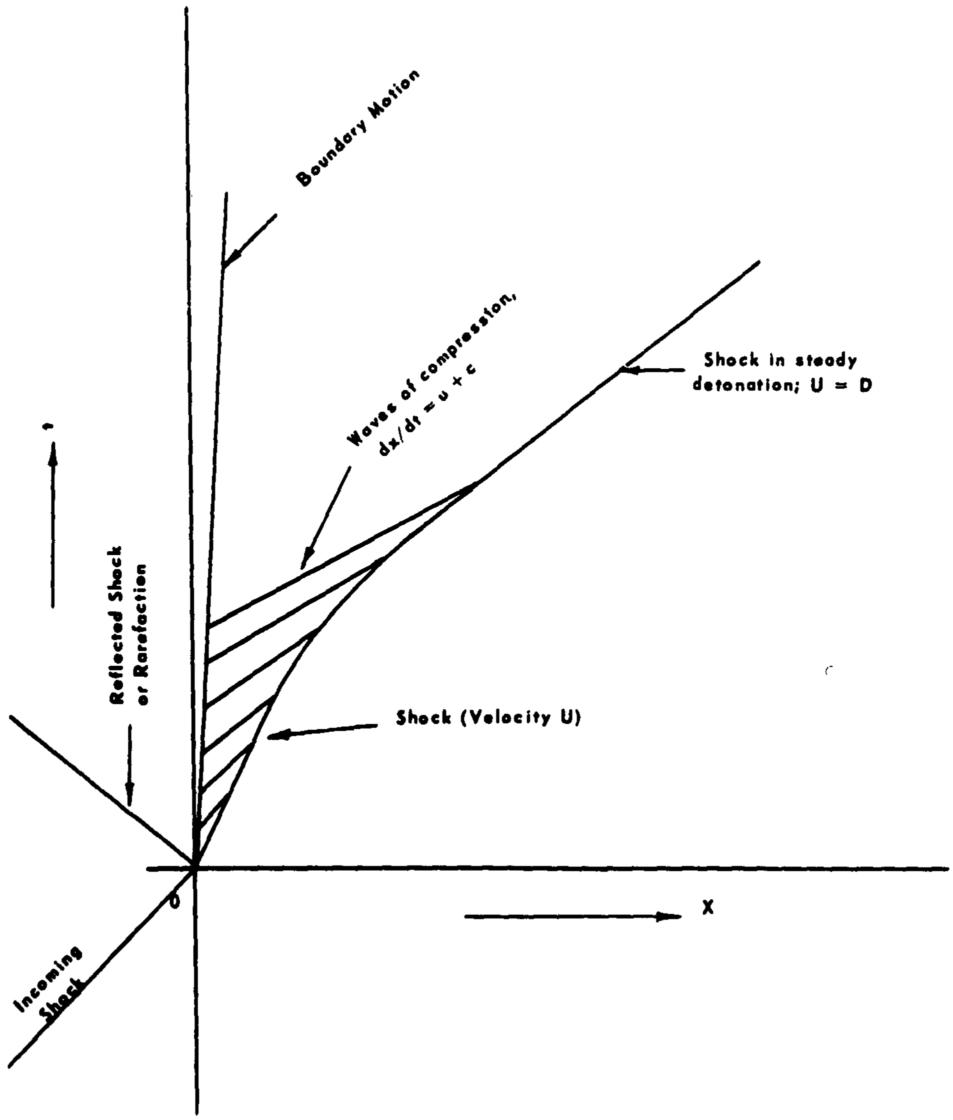
Boundary Motion
Waves of compression,
dx/dt = u + c
Shock in steady
detonation; U = D
t
Reflected Shock
or Rarefaction
Shock (Velocity U)
0
X
Incoming
Shock

Figure 1

PROBLEMS RELATED TO THE BALLISTIC TESTING OF ARMOR WELDMENTS

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The ballistic qualification testing of welding procedures originated during late 1941 and early 1942. At that time a change was being made from riveted construction to welded construction and it was necessary to find some way of assuring good weld quality. It was felt that this qualification should include some type of ballistic test and that the welds should be such as to be under a restrained condition so that radiographic examination could be applied to determine whether a contractor could produce sound welds and also so that the welds would simulate actual conditions for test.

Many preliminary tests were made on various types of plates to arrive at an acceptable type of qualification test plate. Among the plates tried were those with a weld in the shape of a Y, a T, and an H as well as a double I. At first all of these plates were tested by firing armor piercing projectiles to strike the weld with the plate positioned at about 45° obliquity to the line of fire. It was found, however, that the armor piercing projectiles tended to give complete penetrations and distortion of the weld so that a good interpretation of the results could not be made. A proof projectile was therefore adopted for testing plates of 1 inch or greater thickness since it would impart shock forces to the weld without penetration. The proof projectile used then as well as now is a flat-nosed slug made from mild steel bar stock. When it impacts the weld it flattens up to some degree, depending upon velocity, and generally causes some cracking in the welds.

After extensive preliminary tests the H plate was adopted for all qualification testing as the most adaptable both to radiographic and to ballistic testing. As most of you may know the two leg welds of such a plate are welded first and the crossbar last to produce weld restraint; the completed plate is 3 feet square. Figure 1 shows the rear of a typical 1½-inch H plate after being subjected to two impacts by the 75 mm proof projectile at a striking velocity of 1200 fps. In front of the plate is shown a 75 mm proof projectile before firing and also the same type projectile after firing. Note that the deformation is very uniform and that the projectile does not break up.

Later on it became necessary to test thinner H plates and tests showed that smaller proof projectiles like the 37 mm would not be acceptable for this purpose as they did not affect a large enough area and tended to give a punching reaction. The use of the 37 mm HE M54 shell was therefore adopted. This shell with a point detonating fuze detonates on contact with the plate, and the blast tends to deform and shock the welds. This test with the 37 mm HE shell is presently used in testing ½-inch welded plates.

Table 1 shows the present ballistic test requirements for various thicknesses of welded plates. It will be noted that the 75 mm proof projectile is used on 1½-inch plates, the 57 mm proof projectile on 1-inch plates and the 37 mm HE M54 shell on ½-inch plates. The velocities and maximum allowable cracking lengths are also shown.

TABLE 1

Requirements for Ballistic Shock Tests for Welded Plates

Thickness of Test Plate, inches	Type of Homogeneous Armor	Projectile	Striking Velocity fps, plus or minus 25 fps	Allowable Weld Cracking, inches, maximum
1½	Rolled	75 mm M1002	1200	15
1½	Cast	75 mm M1002	1050	10
1	Rolled	57 mm M1001	1050	9
1	Cast	57 mm M1001	975	6
½	Rolled	37 mm HE M54	2525	15

The currently used test of an H plate requires the services of about a six man crew. These men are used to position the plate in the plate holding facility, line in the gun, load the powder charge to give the correct velocity, fire the weapon, and obtain velocities. In addition to the fact that the test requires a sizable gun crew, there are certain other disadvantages. It is impossible to control the velocities exactly, so a variation of ±25 fps is allowed under the specification and in a few cases during tests the velocity falls outside this tolerance. The location of impact cannot be completely controlled and this of course has some effect on the test results. In the case of firing a proof projectile, the impact is required to touch or overlap the weld; with the 37 mm HE M54 shell the center of impact must be within 1¾-inches of the center of the weld. Even slight variations in impact location make a difference in performance. When the 37 mm HE

M54 shell is used there are of course slight variations in fuze functioning time and this can affect the results obtained.

The ballistic test of H-welded plates as presently conducted does have certain advantages. It provides a considerable length of weld for test, which gives the contractor experience and makes a better test possible. The test simulates the kind of shock that welds must undergo in actual service and therefore provides a good measure of expected weld performance. The test is such that it can be applied to small structures or even complete vehicles and therefore consistent data can be obtained on all test items. The test method is adaptable to conducting shock tests of welded joints at all temperatures. Of course one natural advantage is that a large amount of test data has been accumulated on the present type of test and therefore comparisons with past performance can easily be made.

To show the way in which present test requirements were established it can be mentioned that when the shock test for 1-inch rolled H-welded plates was developed the 57 mm proof projectile was fired at a group of 22 H-welded plates to establish the test criterion. At a striking velocity of 1050 fps it was found that if an 8-inch length of crack was set as a limit seven of the plates would fail, whereas if 6 inches was set as the cracking limit three plates would fail. To assure good welding it is considered desirable to have a failure criterion which will reject between 15 and 25% of the welding procedures submitted. Consequently 9 inches is the cracking limit in the present specification requirement for 1-inch rolled welded plates when tested with the 57 mm proof projectile at 1050 fps striking velocity.

Figure 2 shows a 1½-inch rolled armor H-welded plate that was tested as part of a program to study ferritic welding both at normal and low temperatures. This plate has four impacts on it with the 75 mm proof projectile fired at a striking velocity of 1200 fps. Note that the plate has been severed along one leg weld after the fourth impact. This test was made at normal temperature. Some slight variation in impact location can be noted.

Figure 3 shows another plate from the program just mentioned. This plate is a 1½-inch cast ferritic welded plate tested at -40°F with the 75 mm proof projectile at 1050 fps striking velocity. It will be noted

that failure initiated at the weld but extended out into the plate in several directions. This extreme cracking of the armor is of course the result of the effect of low temperature. The extreme failure develops in the armor because of the low resistance of the armor at low temperatures to the propagation of a crack. This plate is a good illustration of one type of failure which can occur especially at low temperature.

Figure 4 shows a 1½-inch aluminum H-welded plate which was tested with the 37 mm HE M54 shell with point detonating fuze at a striking velocity of 2525 fps. This test was used since the plate is equivalent in weight to a ½-inch steel armor plate which is tested in this manner. Note that no cracking occurred.

Figure 5 shows another 1½-inch aluminum H-welded plate tested in the same manner. In this case extreme failure of the welds occurred on two impacts. It may be noted that the weld reinforcement on this plate was not as great as on the previous plate shown.

Recently a number of tests of right-angle-welded corner joints have been made. These tests for the most part have been for the purpose of comparing fillet weld sizes to determine whether smaller fillets can be used to reduce fabrication costs. The problems in testing such corner joint structures are mainly those of providing proper support and obtaining good impact location. We have been reasonably successful with both of these problems, as the following three figures will demonstrate.

Figure 6 shows the method of support used in positioning the corner joints for test. The corner joint shown is of ½-inch material and has been subjected to three impacts with the 37 mm HE M54 shell at a striking velocity of 2525 fps. This welded corner joint was tested so that the weld reacted in shear but it is also possible to test the weld in compression or tension by changing the position of the corner joint.

Figure 7 shows two corner joint samples, both of which were tested so that the weld reacted in shear. Note that good impact location was obtained and cracking appears uniform in length for various impacts.

Figure 8 shows a corner joint made of 1-inch armor which was tested with the 57 mm proof projectile so that the weld reacted in tension. There

was some slight variation in impact location but the cracking which developed was about the same on each of the two impacts.

Two-inch welded strips have been of some use in testing welds. Using the velocity at which fracture occurs this method is suitable for testing 2-inch thick welded armor strips to show differences in ballistic shock resistance between weld metals as well as welding procedures. Strips used are 2-inches thick, 3½ inches wide and 18 inches long, and for one given condition are cut from a single plate or similar plates. Testing has been conducted with the samples at –40° using 57 mm proof projectiles. For one group of samples tested the zone of mixed results was 671 fps to 725 fps based on complete fracture. This type of test could be used as a supplement to H-plate and double-I-welded plate tests.

Figure 9 shows the method of support used in testing the 2-inch welded strips. The strip is wedged into a slotted plate which is supported in the plate holding facility. Figure 10 shows a group of the 2-inch welded strips after test.

Many different types of welded structures have been tested, each one under a different set of conditions. Recently a Marine Corps LVTP-X2 hull was tested at –40°F for shock resistance of the welded joints and armor. The test was performed in the climatic hangar at Eglin Field, Florida, where it was possible to shock the welds inside the hangar by containing resulting fragments by armor shields and armor plate laid on the floor of the hangar. The shock test was given with 37 mm HE M54 shell with the M56 point detonating fuze. Impacts were placed along the welded joints on each side of the hull to compare incomplete and complete penetration welded joints. Incomplete penetration joints were on one side of the hull and complete penetration joints on the other side. The incomplete penetration joints performed satisfactorily based on a comparison with the complete penetration joints. The joint which gave the worst performance was between the lower hull side plate and the sponson floor plate where the reaction to shock is of the tension type.

Figure 11 shows a view of the floor plate of a German Royal Tiger tank hull after test against a land mine containing a 12-pound explosive charge. Note that failure has taken place in the welded joint joining the 40 mm forward floor plate to the 25 mm rear floor plate. Some cracking may also

be noted in the thinner 25 mm rear floor plate.

Figure 12 is a view of the results of detonating another mine containing a 12-pound explosive charge against the same German Royal Tiger tank hull. The area tested in this case was the forward part of the 40 mm floor plate. Note the weld cracking in two joints near the detonation.

In an effort to obtain a more uniform and economical means of testing welding procedures and armor, the explosion bulge test method is presently being studied. The explosion bulge test consists of the static detonation of a bare 50/50 pentolite explosive charge at a specified distance from the test sample. The sample is supported by a steel die having either a 12 in. or a 16-in. circular opening, with the size depending upon the thickness of the sample being tested. The blast wave caused by the explosion exerts uniform stress over the sample area, forcing it into the die opening. Substantially equal strain values are considered to exist in the central pole area (about 3 inches in diameter), gradually diminishing to zero where the plate is supported on the die ring.

The advantages of this type of test are its ability to cause uniform shock loading over a fairly large area, easily reproducible test parameters, economy because of smaller scale samples, and its simple procedure. Thus two disturbing variables present in existing ballistic tests are eliminated: (1) the inability to predict and reproduce hit locations, and (2) the difficulty in repeating definite velocities.

Figure 13 shows the die arrangement for explosion bulge testing. As can be seen the die rests on a solid armor plate which provides a firm level foundation. The steel die on which the sample rests is composed of two sections, each 3 in. thick, either 20 in. or 24 in. square, and having either a 12 in. or 16 in. diameter hole cut from the center of each section. The edge of this hole in the top section is rounded to prevent cutting the sample when it is forced into the die by the blast wave. This die arrangement regulates the diameter of the bulge and permits a balanced biaxial loading condition. When 20 in.-square plates are tested, approximately 60% of the sample area is supported by the die, the remaining 40% being allowed to form the bulge.

The explosion bulge test consists of the following sequence of events. The samples are conditioned in the temperature cabinets at the proper test temperatures until it is certain that the temperature is uniform throughout the samples. At this time, samples are removed from the cabinet singly, carried to the test site, and placed on the die. The cardboard box used to regulate standoff is positioned over the sample and the die. The pentolite charge is then placed on the cardboard box over the center of the sample. An electric blasting cap is inserted in the pentolite wafer and when all personnel are under cover the charge is detonated.

Figure 14 shows the complete arrangement for the explosion bulge test. Note that a sample is in place on the die, the cardboard box is in place, and the pentolite charge is ready for detonation on the cardboard box.

In the explosion bulge test, samples can be evaluated by several means. The thickness strain which the sample undergoes before failure is one method. Thickness strain is determined by accurately measuring the sample thickness before test and again measuring the thickness after test. The percentage reduction in thickness is a measure of the strain the sample has been able to withstand. The amount of bulge is another measure that can be used and the extent of cracking is a third.

Figure 15 shows the type of deformation that can be obtained on samples. The samples shown were 1 in. thick and were subjected to three 9-pound charges detonated at 15 in. standoff with the samples mounted on a 16 in. die.

The next three figures show grade 230 ferritic butt-welded samples tested by the explosion bulge method with each sample at a different temperature. Figure 16 shows a sample tested at +30°F with two 7-pound pentolite charges at an 18-inch standoff. Some cracking in the weld can be noted. Figure 17 shows a sample tested at 0°F with two 7-pound pentolite charges at the same 18-in.standoff distance. The weld in this case has been completely severed. Figure 18 shows a sample tested at -100°F with one 7-pound pentolite charge at the same 18-inch standoff distance. In this case the sample has completely shattered, for the armor is brittle at this temperature. The weld was apparently brittle too, as cracking has occurred in the weld. These three figures show very well

the type of transition performance obtained with the explosion bulge test.

Explosion bulge tests have been made on one group of H-welded plates and the results were promising. Further tests of H-welded plates should be made to determine whether this test method can be used on such samples.

Figure 19 shows a slot-welded specimen which was one of a group prepared for test by Detroit Arsenal in an attempt to determine whether a restrained joint sample could be used. This sample was a 1/2 in.-austenitic welded plate tested with three 3-pound pentolite charges at a standoff distance of 24 in. Note that cracking occurred for almost the full length of the weld.

One big advantage of the explosion bulge test is that only three people are required to carry it out.

In this paper an attempt has been made to acquaint you with the various types of methods of ballistic testing welding procedures and to point out their advantages and disadvantages. It is hoped that this purpose has been achieved.

Fig 1 1½-In. H Plate after Two Impacts with 75 mm Proof Projectile

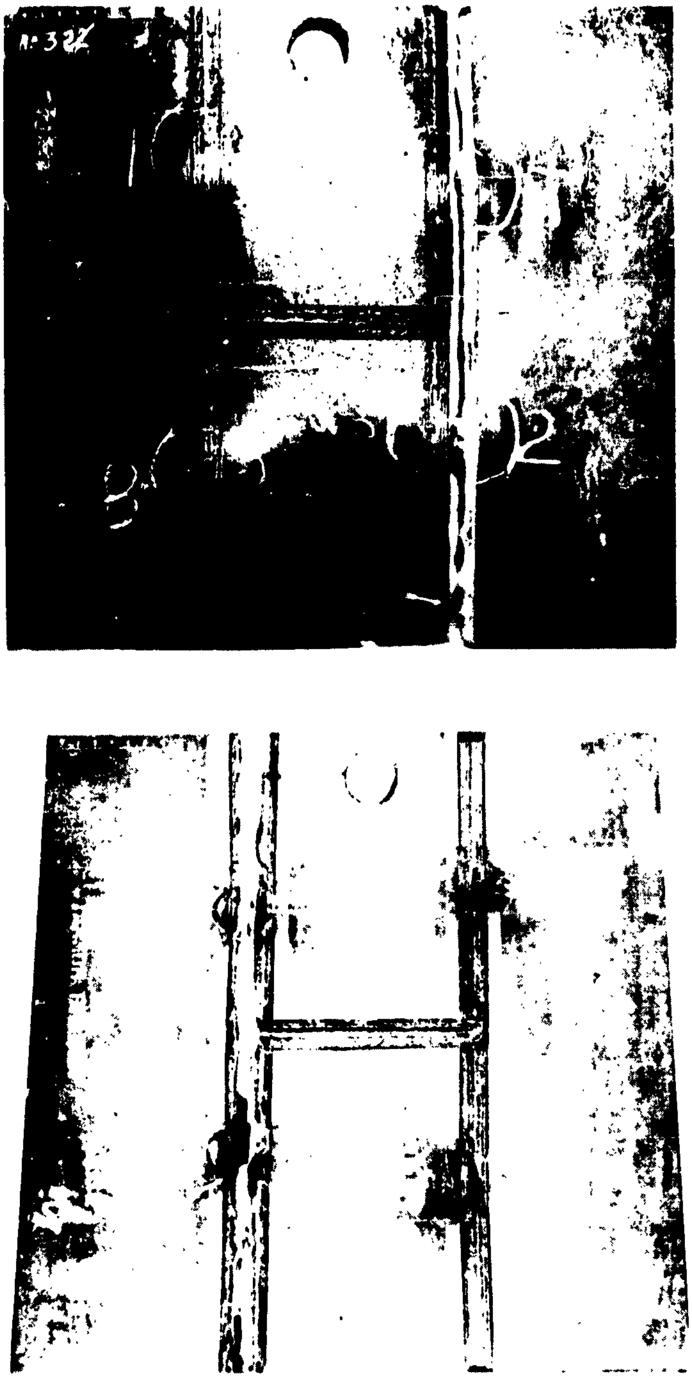

Fig 2 Front and Back View of 1½-In Rolled Ferritic Welded Plate after Ballistic Test at Normal Temperature with M1002 75 mm Proof Projectile

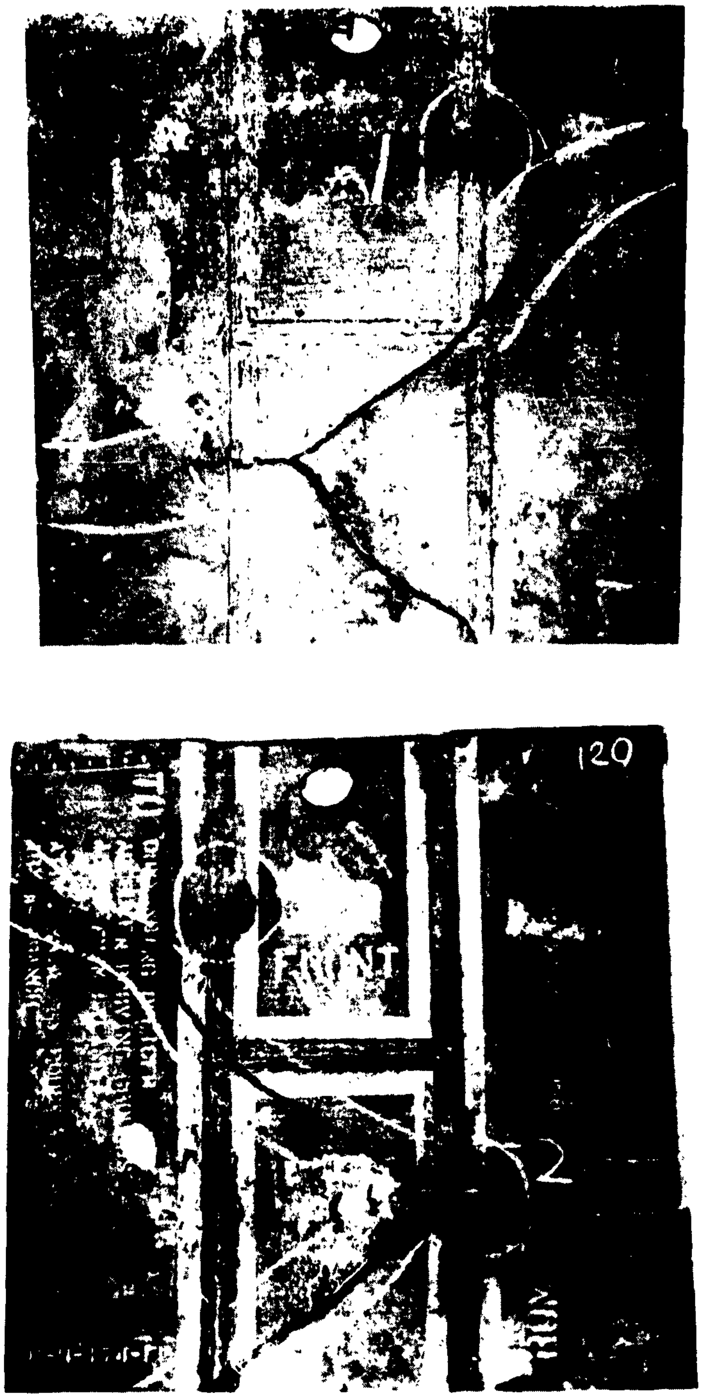

Fig 3 Front and Back View of 1½-In Cast Ferritic Welded Plate after Ballistic Test at -40°F with M1002 75 mm Proof Projectile

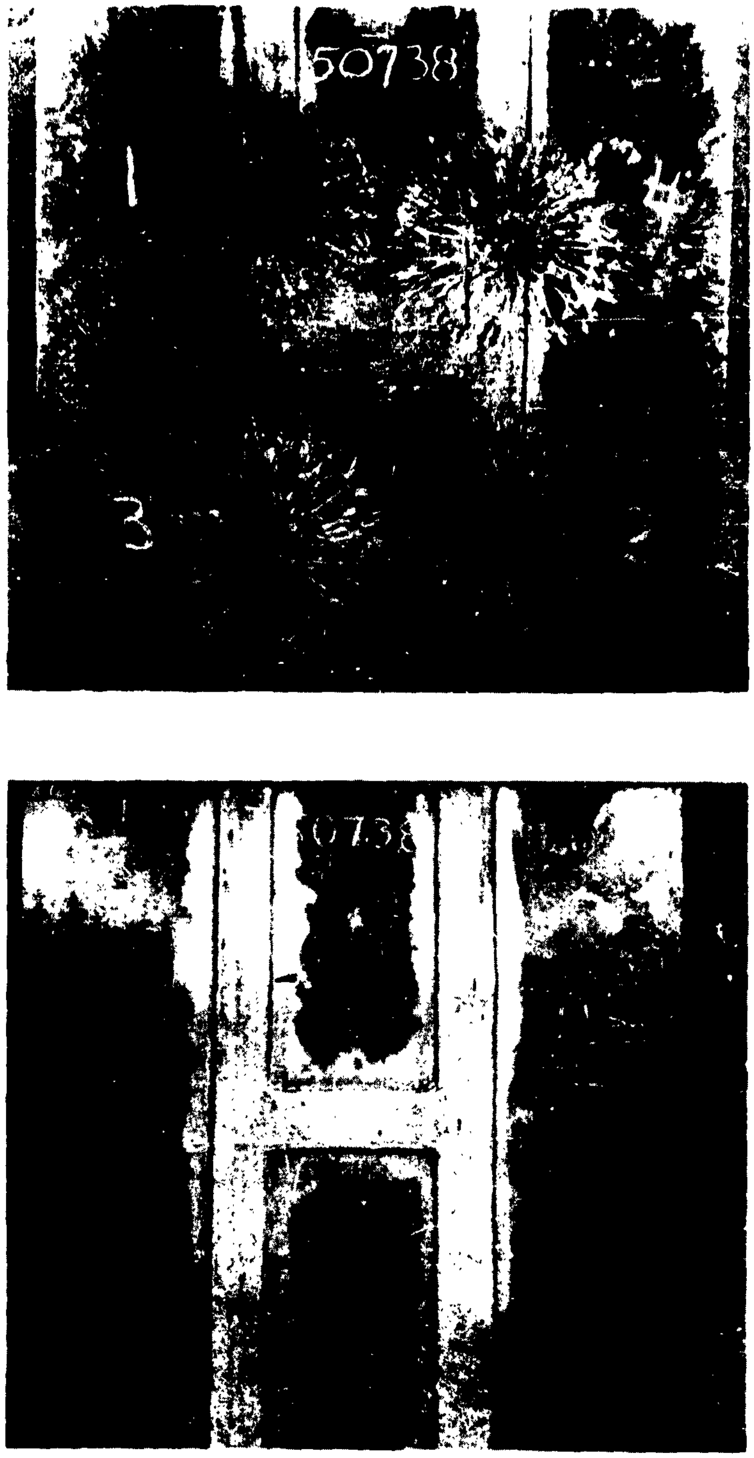

Fig 4 Front and Rear Views of $1\frac{1}{2}$-In. Aluminum H-Welded Plate after Ballistic Attack by Four M54 37 mm HE Projectiles

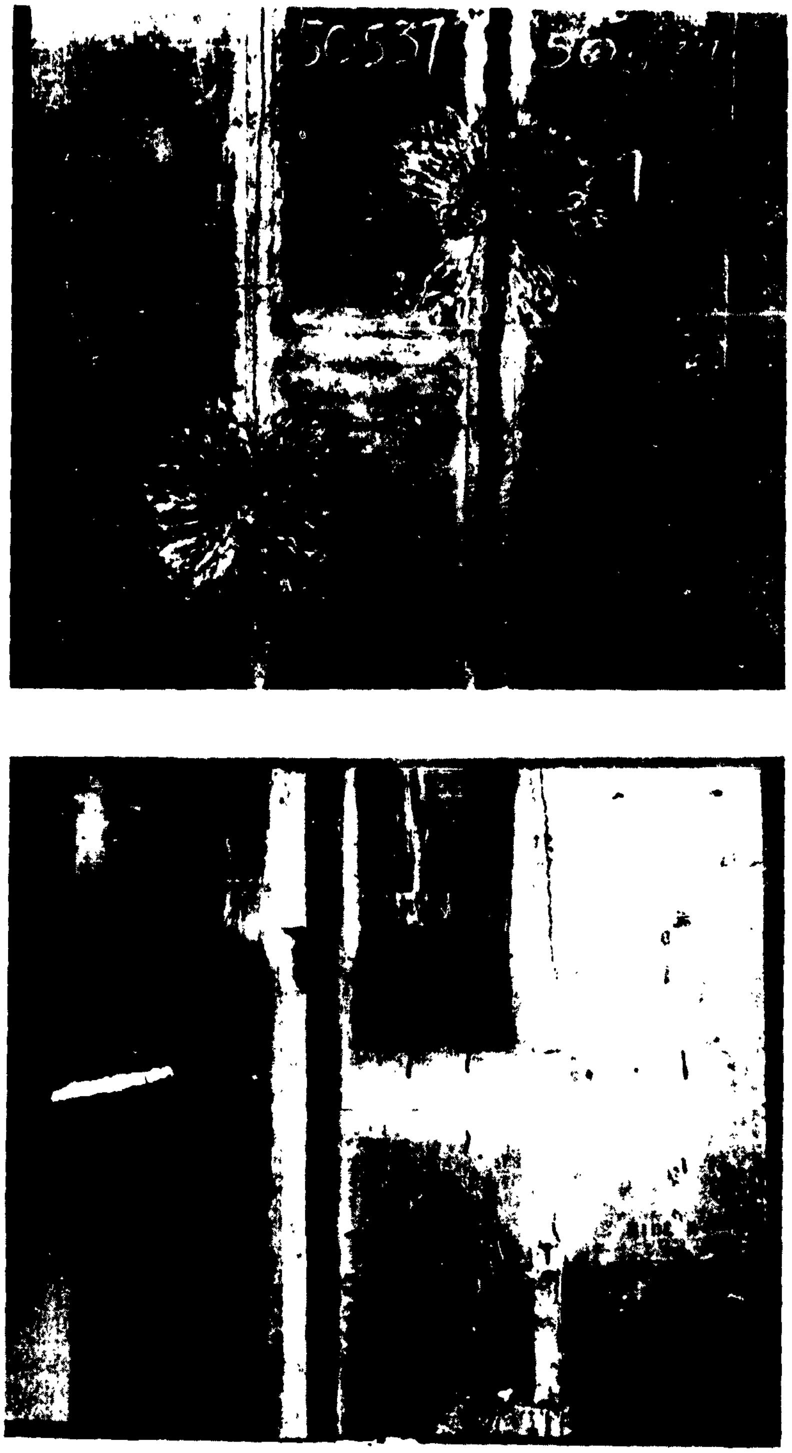

Fig 5 Front and Rear Views of 1½-In. Aluminum H-Welded Plate after Ballistic Attack by Two M54 37 mm HE Projectiles

Fig 6 Test Setup for Corner Joint Weldments Showing Sample after Three Impacts by M54 37 mm HE Projectile with M56 PD Fuze (Sample shown mounted in jig as seen from three-quarter front view)

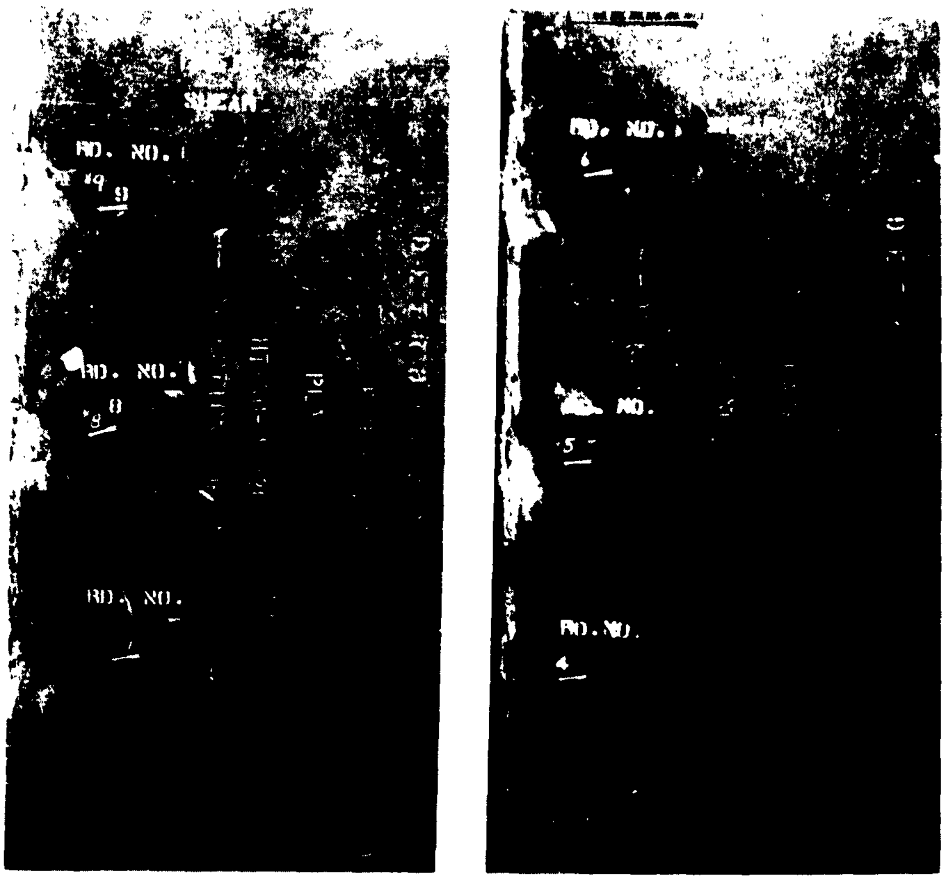

Fig 7 Front View of Two Samples Tested for Shear. (Sample on left has specification size 1/2-in. weld reinforcement and sample on right has reduced 3/8-in weld reinforcement)

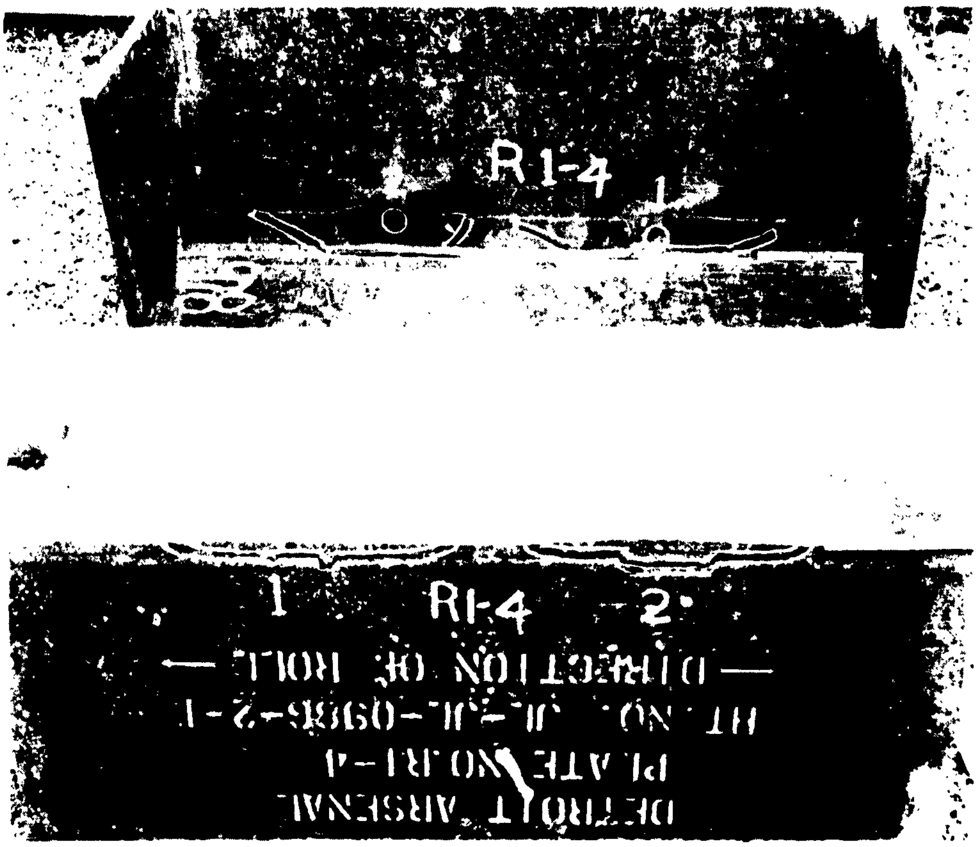

Fig 8 Front and Back Views of Sample Fabricated with 1-In.Rolled Armor, Tested Ballistically in Tension (Weld reinforcement-fillet-reduced size, 3/8 in.)

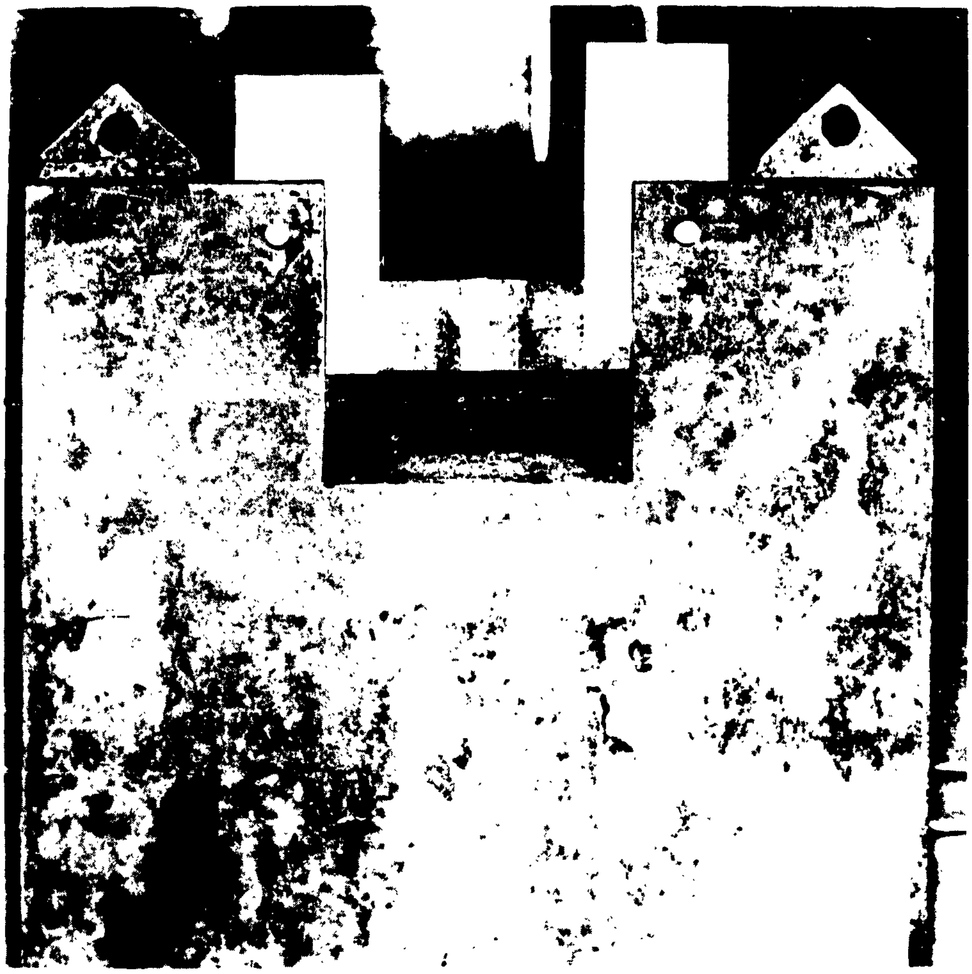

Fig 9 Method of Mounting 18 In. × $3\frac{1}{2}$× 2 In. Welded Strip for Ballistic Shock Test at -40°F

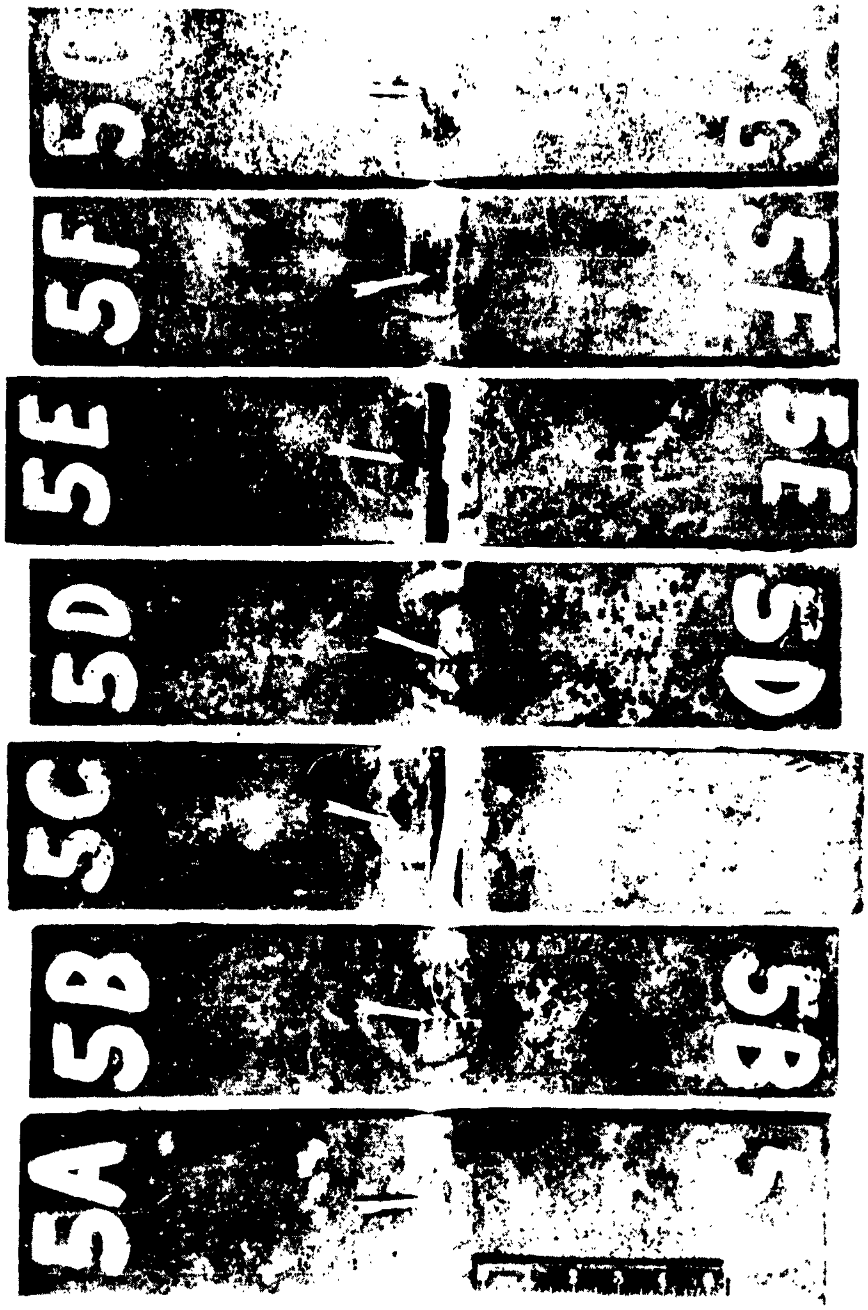

Fig 10 Front View of 18 In. × 3½ In. × 2 In. Welded Strips Cut from Plate Number 5 and Tested with the M1001 57 mm Proof Projectile

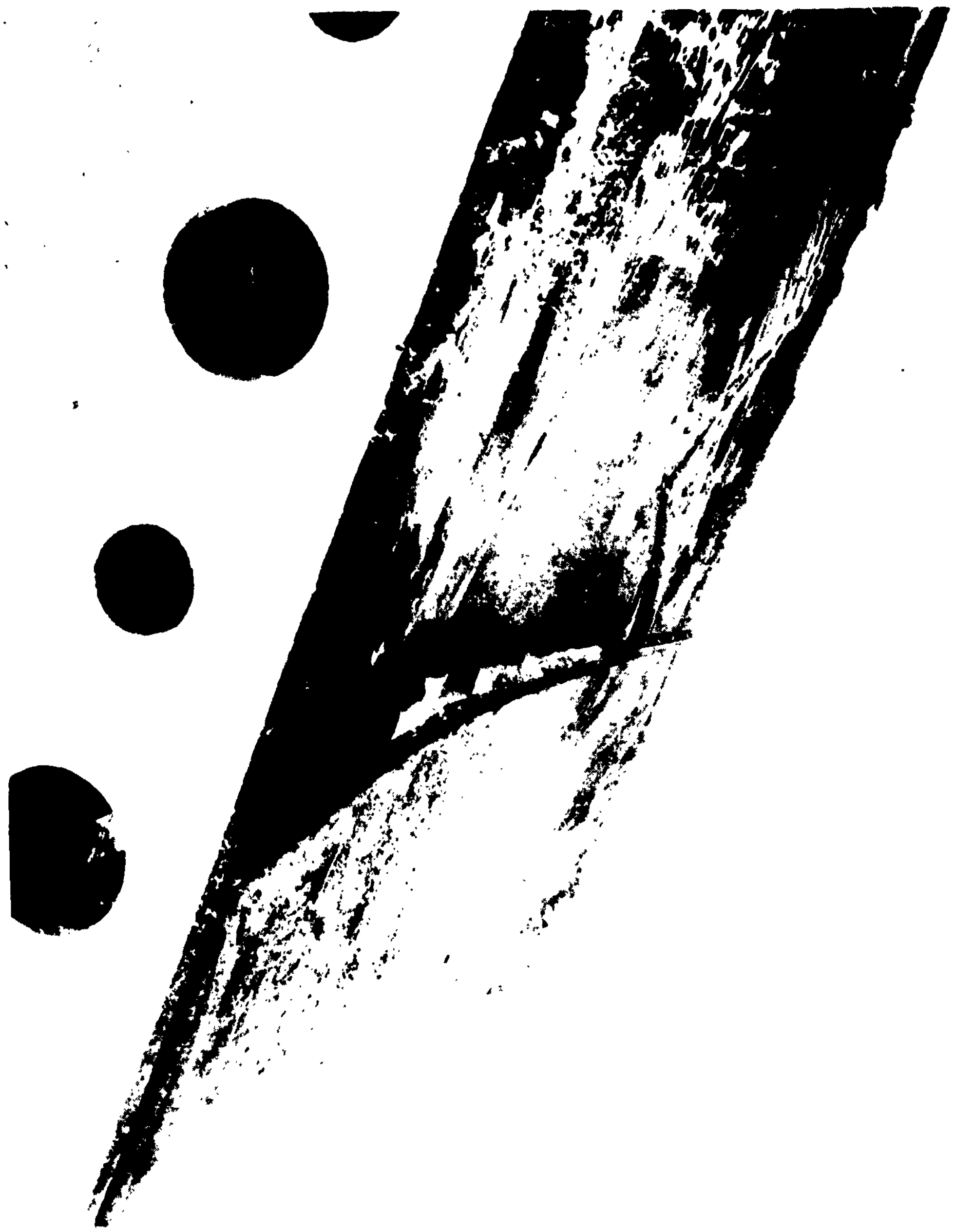

Fig 11 Underside View of Floor Plate on German Royal Tiger Tank Hull after Detonation of One T6E1 Anti-Tank Mine 18 in Below Floor Plate (Round No. 2)

Fig 12 Underside of Front Floor Plate, Right Side (40 mm thick) of German Royal Tiger Tank Hull after Detonating One T6E1 Anti-Tank Mine 18 in. below Floor Plate (Round No. 1)

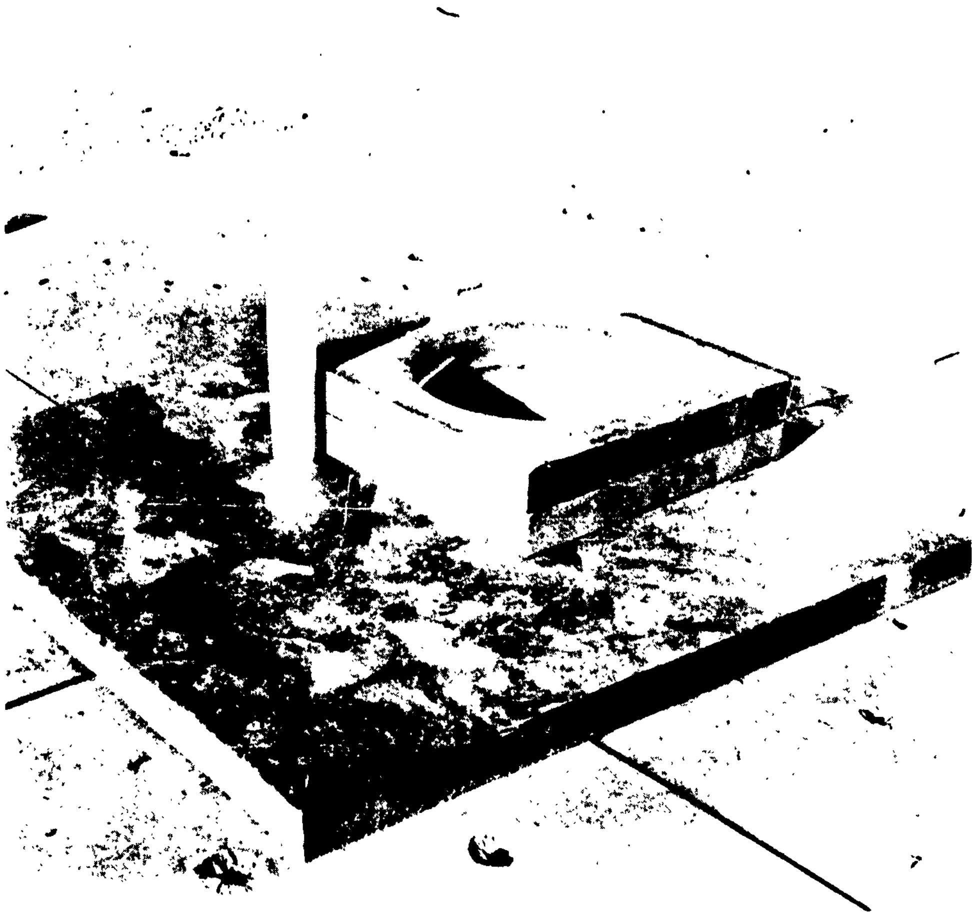

Fig 13 Three-Quarter View Showing Die and Base Plate Used in Explosion Bulge Test of 1-In. Welded Armor Samples from Battelle Memorial Institute

Fig 14 Cut-Out View of Explosion Bulge Test Setup Showing the Base Plate, Die with Sample in Position, Cardboard Box Used for Standoff, and Pentolite Charge with Blasting Cap in Place

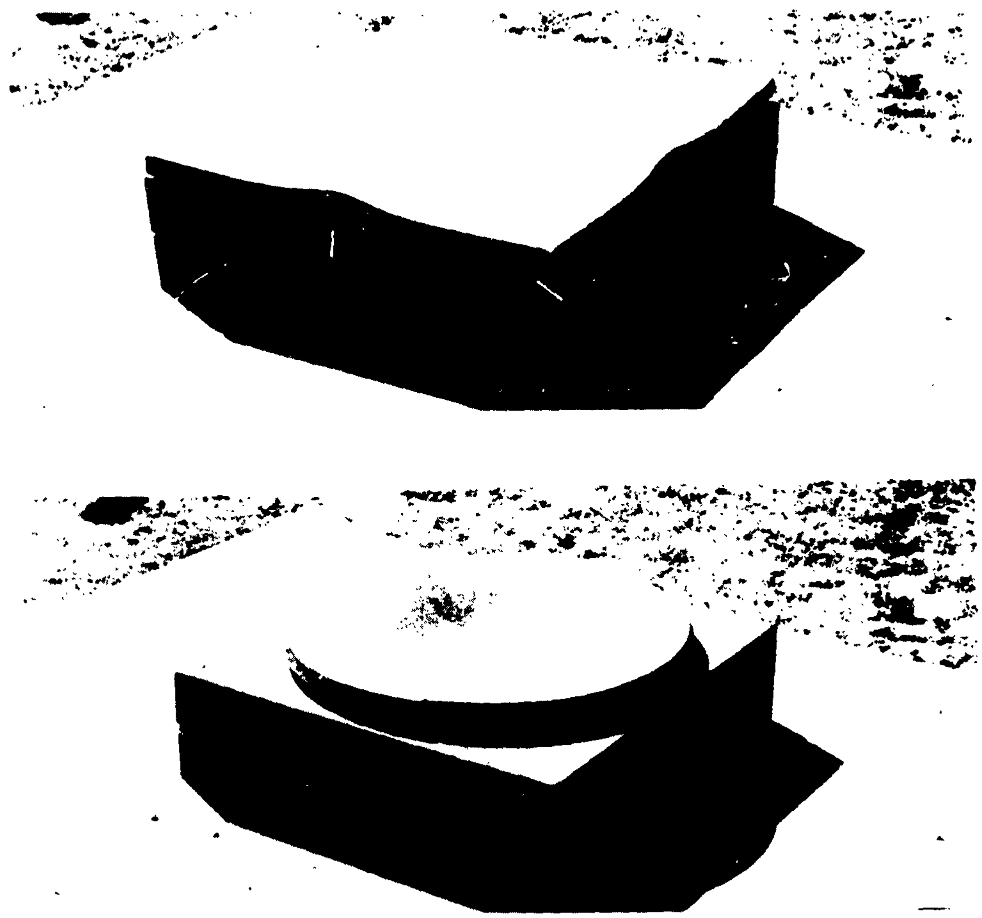

Fig 15 Explosion Bulge Test—Comparison of Hold-Down Characteristics of Circular and Square 1-In. Plates after Being Subjected at 75°F to Three 9-Pound Charges of Pentolite at 15 In. (A 16-in. die was used)

Fig 16 Explosion Bulge Test of 1-In. Welded Armor Samples from Battelle Memorial Institute (24-in. square plate; grade 230 weld; impacted with two 7-lb pentolite charges; temperature +30°F; 18-in. standoff; 1¾-in. bulge after two charges)

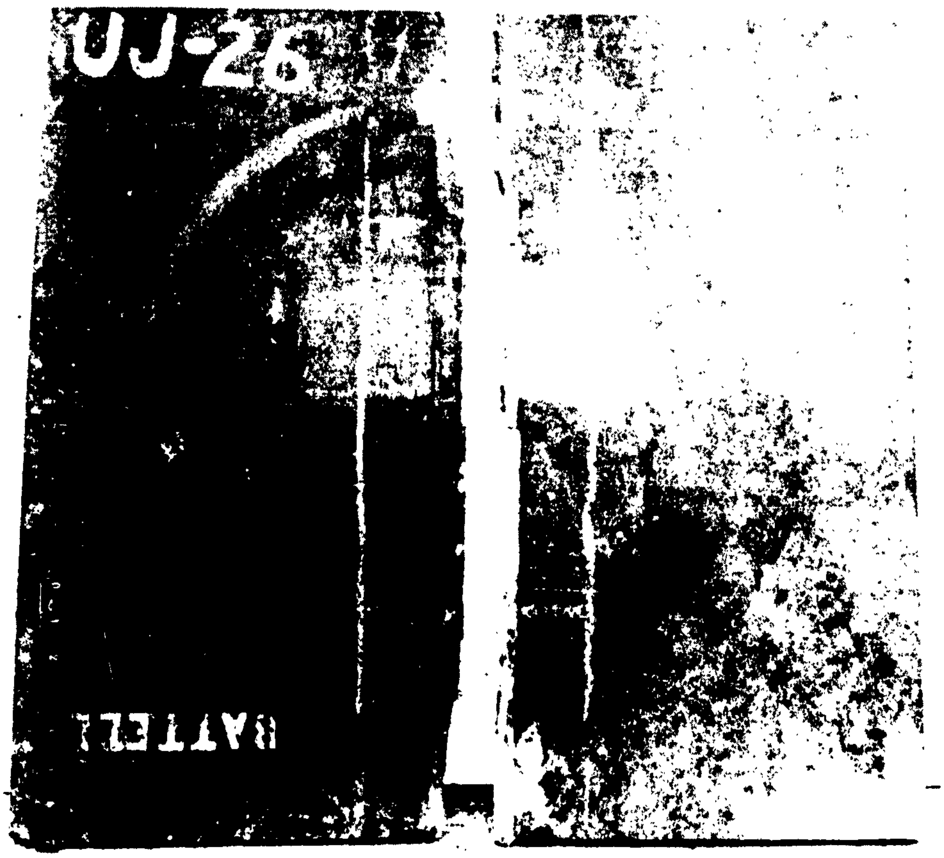

Fig 17 Explosion Bulge Test of 1-In. Welded Armor Samples from Battelle Memorial Institute (24-in. square plate; grade 230 weld; imparted with two 7-lb pentolite charges; temperature 0°F; 18-in. standoff; 1 5/8 in. bulge after two charges)

Fig 18 Explosion Bulge Test of 1-In. Welded Armor Samples from Battelle Memorial Institute (24-in. square plate; grade 230 weld; impacted with on 7-lb pentolite charge; temperature -100°F; 18-in standoff; shattered after one charge)

Fig 19 Development of Bulge Explosion Test Armor and Welds (20-in. square plate; austenitic welded; impacted with three 3-lb pentolite charges; temperature +80°F, 24-in. standoff; 1 5/8 in. bulge and 14 1/2 in. weld zone cracking after third impact)

SOME PROBLEMS AND TECHNIQUES IN THE CAST-LOADING OF AMMUNITION

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The Ordnance Corps is extremely interested in any method which will make it possible to increase the quality of cast-loaded ammunition and at the same time increase production yields. Imperfectly loaded shell are a problem for a number of reasons, some of which follow:

1. Sizable cavities or voids in the cast explosive have been thought unsafe, in that they cause the collapse of the explosive or the practically adiabatic compression of any entrapped air. It was postulated that the resulting temperature increase might be enough to result in premature detonation of the shell. Recent research, however, has indicated that this mechanism is probably not responsible for premature detonations (Ref 4).

2. Cavities, voids, and poor density of the cast explosive reduce the payload and would decrease the efficiency and lethality of the round.

3. A poor cast loading job may adversely affect the center of gravity, and thus the stability of a round, resulting in a target miss.

4. Finally, and this is becoming increasingly important, as witness the great deal of discussion concerning it at this meeting, are the effects of inhomogeneities in cast explosives on the shaping of detonation wave fronts. In a number of recent papers and in the views of many of the scientists at this conference, irregularities in the explosive due to imperfect casting can wreak havoc with a detonation wave front, negating most of the benefits which might be achieved in the design of a device to produce a shaped wave.

It is the purpose of this paper to outline a number of the techniques which are in use and which have been used to cast-load ammunition. Further, a method will be described which has been proposed to produce casts of high enough quality to enable successful use by experimenters and production engineers. This method would eliminate or minimize inhomogeneities in the casting of explosive charges.

In order to demonstrate a little better what the loading plant is up against in attempting to obtain good casts, Figures 1, 2, and 3 show rounds containing flaws in the cast explosive. Figure 1 represents a number of voids or cavities distributed throughout the explosive. These were probably caused by too high a pouring viscosity and/or the use of explosive containing large amounts of air. Figure 2 shows an elongated shrinkage cavity which may have been caused simply by a draft of cool air inadvertently trained on one side of the shell during cooling. Figure 3 illustrates a typical "piping" cavity caused by natural shrinkage of the explosive towards the shell wall during cooling. The "pipe" is the result of the freezing up of the explosive in the pouring funnel which has been inserted into the throat of the shell. This freezing interferes with the feed which would have filled in the shrinkage cavity.

The present production line method of eliminating these large shrinkage cavities in TNT-loaded shell consists of a modification of the simple one-increment pour and is known as "core melting." Since TNT shrinks about 9% upon freezing (compared to 4% for Composition B) it is usually poured as a slurry containing about 30% solids. This tends to reduce shrinkage, but in shell of caliber 90 mm and larger corrective action to eliminate central piping cavities is usually still required. In core melting the item to be loaded is filled using a one-increment pour. When the shell cools, the central longitudinal cavity shown in Figure 3 is formed. A steam-heated copper probe one inch in diameter is then introduced into the shell, melting the explosive core at the rate of about 3 inches per minute down to the bottom of the shrinkage cavity, after which TNT is poured into the shell to fill the core and allowed to cool (Fig 4). A single probing is adequate for TNT-loaded items up to about 120 mm in caliber (approximately 7.5 lb of charge). For larger shell, up to 155 mm in caliber it is necessary to use the hot probes twice, with filling and solidification in between. The depth of the first probe is about 14 inches from the top of the shell and the depth of the second probe about 6 inches.

A different set of techniques is used for loading Composition B. In shell larger than 120 mm, a two- or three-increment loading procedure may be used. Figure 5 indicates the existence of poor fusion between the various increments of Composition B. Central piping cavities are also apparent in Composition B-loaded shell but the core melting technique

successfully used in TNT loadings is not practical with Composition B. The reason for this is that while TNT can be core melted at the rate of 3 inches per minute, a Composition B cast will melt at the prohibitively slow rate of 1/30 inch per minute. Therefore, the Composition B hot probe technique is used, as follows: Immediately after the Composition B is poured, the steam-heated copper probe is inserted into the explosive to a depth about level with the bottom of the pouring funnel (Ref 1) . As the charge solidifies, the explosive in the funnel (or riser) is kept molten by the probe so that any piping cavitation is immediately filled by the liquid reservoir of explosive in the funnel.

Many other shell loading procedures have been developed. For example, the pellet loading or puddling technique has been used in loading bombs, warheads, or mines or any item which is normally dropped from a plane, launched at low set-back, or which remains stationary prior to initiation. In puddling, a few inches of molten explosive is poured into the item. Pellets or chunks of explosive are then added until they reach the upper level of the molten explosive. Then another few inches of molten explosive is added and this procedure is repeated until the item is fully loaded. This method is tedious and results in a poor quality cast (Fig 6) but it has the advantage of producing an item which can be handled and transported immediately after loading is completed since the item is cooled by the pellets during loading.

Other techniques which might be mentioned in passing include:

1. The Sit-and-Simmer Method

This was a modification of pellet loading used during World War II for loading large bombs. The bomb was filled in one continuous pour and then allowed to "sit and simmer." After a waiting period the top crust was broken and pellets were dropped into the liquid and air space uncovered by the broken crust. Production was greatly increased but at the sacrifice of charge quality.

2. Centrifugal Casting

This procedure consists of rotating the item to be loaded together with an explosive reservoir at speeds of 200 to 350 revolutions per minute. This technique is still in the early stages of experimentation.

3. Jolt Loading

This technique has been used to remove entrapped air bubbles by jolting the item at the rate of 2 jolts per second for 10 seconds in a Syntron Jolting Machine.

4. Vibration Loading

In this method, a Baldwin oscillator has been used to eliminate entrapped air bubbles thus making this procedure useful for casting very viscous explosives.

5. The Molded TNT Technique (Ref 2)

This method is widely used in Belgium for loading TNT. About 15% of the shell cavity is filled with molten explosive and a long shaped core of solid TNT is set into it. The core is held in place about 10 seconds and then the rest of the cavity is filled with molten TNT. The TNT core is produced by individually pressing very small increments of molten TNT in a water-cooled cylinder.

It should be emphasized that none of the procedures described is entirely satisfactory for the mass production of explosive casts of very high quality which are uniform in composition, high in density, and free of voids and shrinkage cavities. Yet the more effective of these methods do produce items of ammunition which are acceptable for Ordnance Corps use.

With the advent of techniques for shaping detonation wave fronts it became clear that methods which had heretofore been good enough would have to be modified to give much better casts. The effectiveness of these wave-shaping devices depended on the attainment of casts with practically no flaws or density or composition gradients. The method developed to produce such casts is known as Single-Pour Controlled Cooling or SPCC for short. At present, there is a pilot-scale plant in existence at Iowa Ordnance Plant which is capable of loading up to 230 rounds in one completely automatic cycle.

SPCC is distinguished by the fact that it alone of all the methods

TABLE 1

Typical Operating Conditions and Cooling Cycle Times

Round	Total Cycle Time (hr)	Radiant Oven No. 5 on (hr)	Oven No. 5 off (hr)	Water Temp °F	Water Level inches	Steam Pressure psig
155 mm*	5 1/2	4 1/2	1	75	10	50
155 mm**	5 1/2	5 1/2	0	120	10 for 2 1/2 hrs 8 for 1 hr 6 for 1 hr 4 for 1 hr	50
8 inch*	10 1/2	9	1 1/2	70	12 for 7 hrs 9 for 3 1/2 hrs	50
4.2 inch*	3	2	1	75	5	50
105 mm*	3	2	1	75	5	50
105 mm**	3 1/2	2 1/2	1	120	5	50
75 mm**	1 1/4	1/2	3/4	120	5	50

* TNT Loaded

** Composition B loaded

In all cases the shell obtained by the procedure listed were of uniform, high density, (1.625 ± 0.005 g/cc for TNT; 1.720 ± 0.010 g/cc for Composition B), cavity free and fine textured.

The steam pressures listed result in a temperature of 200°F on the funnel surfaces.

previously discussed completely controls both melting of the explosive and cooling of the loaded item.

The method as it is used at Iowa Ordnance Plant consists of melting the explosive charge in a melt kettle to which a minimum vacuum of 1 cm of mercury absolute pressure has been applied. It has been found that even though vacuum is not used during pouring, casts with evacuated melt approach their theoretical densities and exhibit uniform densities between different shell and within each shell. The shell is filled automatically in one increment and in the cast of TNT loading a continuous crystallizer is used which incorporates into the molten TNT a definite and constant quantity of solid TNT. This has the effect of controlling pour temperature and thus viscosity very closely, and makes for a much more uniform pour.

The controlled cooling is accomplished by partially submerging the loaded shell in water, with the ogive and funnel exposed to the heat of a radiant oven, Figure 7. A temperature of 176°F-195°F is maintained at the funnel throat to keep the reservoir of explosive in the funnel molten. The water level is held constant for experimentally determined periods to allow cooling to proceed regularly and evenly. Table 1 shows a set of typical operating conditions and cooling cycle times for a number of TNT- and Composition B-loaded shell. Iowa Ordnance Plant has reported the following results (Ref 3) with the use of this process. Values for the conventional one-increment loading technique have been included for comparison.

Process	Density, g/cc	Spread, g/cc	% RDX	% Spread
SPCC (TNT)	1.620	0.005	-----	-----
Conventional (TNT)	1.580	0.040	-----	-----
SPCC (Comp B)	1.715	0.010	60.0	4-5
Conventional (Comp B)	1.670	0.050	60.0	10-15

The spread was measured by taking sample cores of explosive from different areas of each shell.

Picatinny Arsenal is presently conducting work to determine whether SPCC techniques can be used to improve standard rounds of ammunition.

The methods used are similar in intent to those described but differ in detail since the Picatinny facilities are purely experimental. For example, copper tubing is used to keep the funnel and ogive portions of the item hot and, in place of water around the lower part of the shell, some of our rounds have been kept warm by means of a thermopanel which acts in effect like a hot plate and transmits heat to the shell walls by conduction. Sample results achieved by procedures used at Picatinny are tabulated below for the casting of Composition B in 90 mm HE shell:

Process	Density, g/cc	Spread, g/cc	% RDX	% Spread
SPCC	1.719	.004	60	4-7
Conventional	1.684	.034	60	0-7

Finally, work on additives for use in decreasing the cooling cycle time is proceeding. Materials such as anthracene 0.2-0.4%, alpha-nitronaphthalene, and 2,4,6-trinitroanisole have been used to prevent cracking. The use of small amounts of ortho- and para-nitrotoluene permits the immersion of the lower portion of the freshly loaded shell in 90°F water instead of 120°F water, thus cutting down cooling time. However, some exudation is experienced with the use of these additives and so the search is continuing for anti-cracking additives which do not cause exudation from the explosive charge. Tests are being conducted with other additives such as nitrocellulose and a number of polyurethanes to improve the cast strength of some of the common explosives.

It appears possible that even though SPCC was developed to meet a very special need, its methods may yet be applied to advantage in the general field of ammunition loading.

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2. *Preliminary Evaluation of Belgian Molded TNT*, Picatinny Arsenal Technical Report 2216, E. A. Skettini, July 1955

3. Dr. L. R. Rothstein and R. L. Holmberg, The SPCC Melt-Pour-Cool Process Research and Development Program (The Shell Loading Process of the Future), Iowa Ordnance Plant, 10 May 1955

4. *Cavity Standards for Cast-Loaded Artillery Projectiles,* Progress Report No. 17, Contract DAI-19-020-501-ORD-(P)-61, Arthur D. Little, Inc., May 1956

Fig 1 Cast-Loaded High Explosive Round Containing a Number of Voids or Air Cavities

Fig 2 Cross-Section of a Cast-Loaded High Explosive Round Showing an Elongated Shrinkage Cavity Down One Side of the Shell

Fig 3 Cast-Loaded High Explosive Round
Containing a Central Piping Cavity

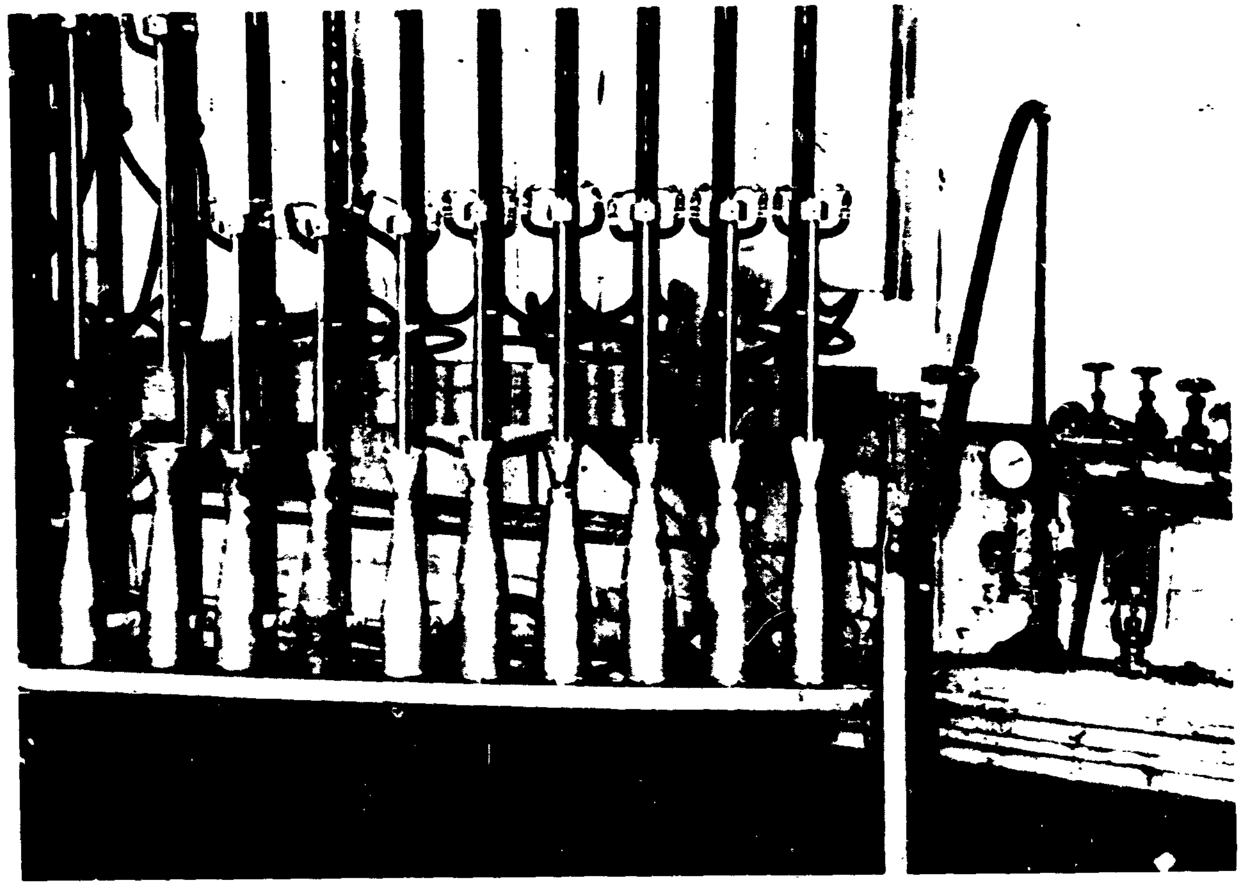

Fig 4 Shell Containing "Piping" Cavities Being Repaired by the Core Melting Procedure

Fig 5 Cast-Loaded High Explosive Round Which Had Been Filled in Three Increments. There is obvious evidence of poor fusion between the increments.

Fig 6 High Explosive Bomb Which Has Been Cast-Loaded by Puddling. The dark areas indicate that molten explosive has not flowed uniformly into the interstices between the explosive pellets.

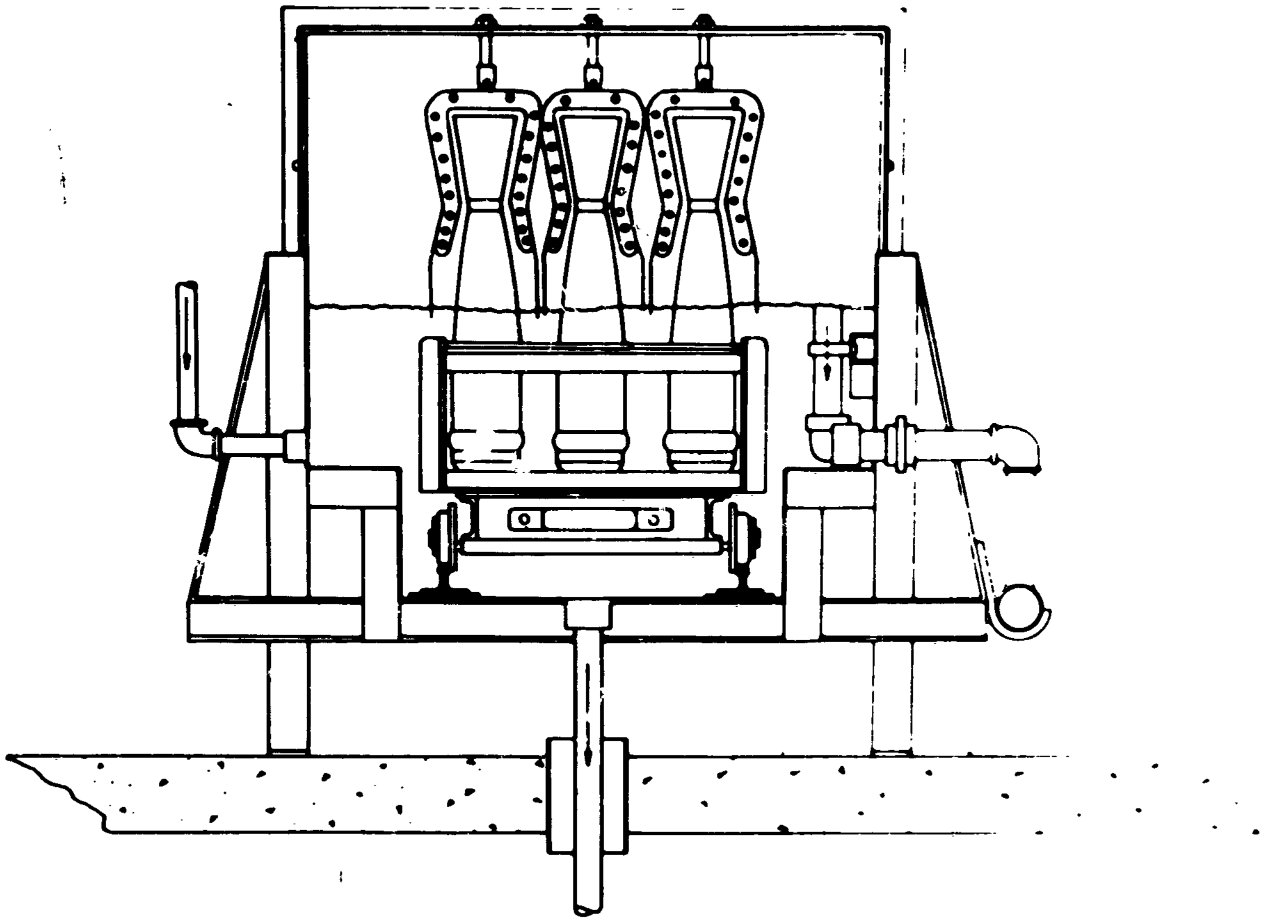

Fig 7 Transverse Cross Section of Pilot Plant Conditioning Oven. Three Shell Being Cooled in the Conditioning Oven. A steam-heated hood keeps the explosive in the upper portion of the shell molten.

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